

Performance of Expanded Polystyrene Insulated Panel Exposed to Radiant Heat

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ABSTRACT

Expanded polystyrene insulated panel is a building material that is manufactured by adhering light gauge sheet metal to both sides of a core of expanded polystyrene. This report examines how the combustible core of expanded polystyrene insulated panel behaves when exposed to a radiant heat source at elevated temperatures.

A number of fires in commercial/industrial buildings constructed from this product, mainly in Europe, have highlighted concerns about its performance and safety. A series of experiments were conducted which simulated the situation of a flue passing through a roof or ceiling in a building that was constructed from expanded polystyrene insulated panel. Specimens of the product were placed immediately adjacent to a stainless steel flue with surface temperatures ranging from 600 – 900 °C approximately. The behaviour of the expanded polystyrene core of the insulated panel was monitored.

The primary conclusion of the project was that, although the expanded polystyrene core of the specimens ignited for the higher flue temperatures, there was no evidence of the combustion spreading through the core. In all cases, the flaming died out after the core had shrunk far enough away from the flue.

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CONTENTS

List of Figures	x
List of Tables	xi
1.0 INTRODUCTION	1
1.1 Background	1
1.2 Report Objectives	2
2.0 LITERATURE REVIEW	2
2.1 Fire Incidents	3
2.2 Fire Fighting	5
2.3 Fire Safety	6
2.4 Fire Testing	8
2.4.1 Insurance Industry	9
2.4.2 ISO 9705 Room/Corner Test	9
2.4.3 Modified ISO 9705 Test	12
2.4.4 European Fire Classes - Euroclasses	13
3.0 EXPANDED POLYSTYRENE INSULATED PANEL	16
3.1 Historical Usage of PIP	16
3.2 Manufacture of PIP	17
3.3 EPS Core of PIP	18
3.3.1 Material Description	18
3.3.2 Manufacture	20
3.3.3 Alternative Core Materials	22
3.4 Combustion of PIP	24
3.4.1 Burning Behaviour	24
3.4.2 Flame Retardants	27
3.4.3 Smoke Production	30
3.4.4 Toxicity	32
3.5 New Zealand Building Code Requirements	32
3.5.1 Control of Internal Fire and Smoke Spread	33
3.5.2 Control of External Fire Spread	35
3.5.3 Outbreak of Fire	36
4.0 EXPERIMENTAL INVESTIGATION	37
4.1 Experimental Apparatus	37

4.1.1	Heat Source	37
4.1.2	Cylindrical Radiator	39
4.1.3	Test Specimens	40
4.1.4	Support Framework	43
4.1.5	Instrumentation	44
4.2	Background Theory - Thermal Radiation	46
4.3	Experimental Methodology	56
5.0	RESULTS	56
5.1	Experimental Observations	57
5.1.1	Experiment No. 1	57
5.1.2	Experiment No. 2	58
5.1.3	Experiment No. 3	58
5.1.4	Experiment No. 4	59
5.1.5	Experiment No. 5	59
5.1.6	Experiment No. 6	60
5.1.7	Experiment No. 7	61
5.1.8	Experiment No. 8	61
5.1.9	Experiment No. 9	62
5.2	Thermocouple Data	62
5.2.1	Experiment No. 6	63
5.2.2	Experiment No. 5	65
5.2.3	Experiment No. 9	66
5.3	Analysis of Data	67
5.3.1	Regression of Core	67
5.3.2	Critical Incident Flux	68
6.0	DISCUSSION	71
6.1	Flue Surface Temperature	71
6.2	Behaviour of EPS Core	72
6.2.1	Production of Combustible Gasses	72
6.2.2	EPS Core Regression	73
6.2.3	Burning Behaviour	74
6.2.4	Sloping Specimen	75
6.2.5	EPS Core Removal	76
6.3	Further Research	76

7.0	CONCLUSIONS	77
8.0	REFERENCES	79
9.0	BIBLIOGRAPHY	88
	APPENDICES	93
A1.0	Thermocouple Data	93
A2.0	Time vs. Melt Distance	95

List of Figures

Figure 2.4.2.1 – The ISO 9705 Room/Corner Test	10
Figure 2.4.2.2 – Calculation of the FIGRA Index	11
Figure 2.4.4.1 – Single Burning Item (SBI)	14
Figure 2.4.4.2 – Loss Prevention Council Corner Test	15
Figure 3.3.1 – Styrene Monomer	18
Figure 3.4.1.1 – Idealised View of Thermal Degradation of Thermoplastic	25
Figure 3.4.1.2 – Energy Feedback Loop Required for Sustained Burning	26
Figure 4.1.1.1 – Burner Box	38
Figure 4.1.1.2 – Photo of Mass Flow Control Unit	38
Figure 4.1.2.1 – Flue and Baffles	39
Figure 4.1.2.2 – Photo of Flue/Burner Configuration	40
Figure 4.1.3.1 – Specimen Preparation	42
Figure 4.1.4.1 – Photo of Dexion Support Frame	43
Figure 4.1.5.1 - Thermocouples	45
Figure 4.2.1 – Electromagnetic wave spectrum	46
Figure 4.2.2 – Thermal radiation wavelength band	48
Figure 4.2.3 – Cylindrical radiator to parallel receiver	52
Figure 4.2.4 – Flue Temperature vs. received Radiation on EPS Core	53
Figure 4.2.5 – Cylindrical radiator to normal receiver	53
Figure 4.2.6 – Temperature vs. Received Radiation at 200 mm	55
Figure 5.2.1.1 – Experiment No. 6 Thermocouple Data	64
Figure 5.2.2.1 – Experiment No. 5 Thermocouple Data	65
Figure 5.2.3.1 – Experiment No. 9 Thermocouple Data	66
Figure 5.3.1.1 – Regression of Core vs. Incident Flux	68
Figure 5.3.2.1 – Time vs. Melt Distance for Experiment No. 6	69
Figure A1.1 – Experiment No. 2 Thermocouple Data	93
Figure A1.4 – Experiment No. 7 Thermocouple Data	95
Figure A1.5 – Experiment No. 8 Thermocouple Data	95
Figure A2.1 – Time vs. Melt Distance for Experiment No. 2	96
Figure A2.2 – Time vs. Melt Distance for Experiment No. 3	96

LIST OF TABLES

Table 3.5.1.1 – Foamed Plastics – Protection from Ignition	34
Table 3.5.2.1 – Acceptable Heat Release Rates for External Cladding Systems	36
Table 5.3.2.1 – Critical Melting Flux	70

1.0 INTRODUCTION

1.1 Background

In the past decade, a relatively small number of fire incidents around the world have highlighted concerns about the fire performance of a commonly used building material, insulated panel.

Insulated panel, also known as “sandwich panel” or “insulating sandwich panel”, is generically a multi-layered product that has three or more layers bonded together (ISO, 1999a). One or more of the layers are an insulating material, while the skins consist of a variety of different products.

Insulated panel is in widespread usage for commercial and industrial applications as a cladding and lining material. Typical examples are in hygiene areas for food processing, cold storage facilities and as external cladding on buildings.

This report focuses on one specific type of insulated panel. This panel has three layers - the insulating material is a central core of expanded polystyrene (EPS) to which light-gauge painted steel skins are bonded to form the so-called “sandwich”. Throughout this report, the term “polystyrene insulated panel” (PIP) will be used to refer to the product.

The bonding of the outer skins to the inner core provides insulated panel with structural properties that are far greater than the individual components of the composite. ‘The flexural strength is achieved by the combined structural action of the rigid facings and the core material’ (Cooke, 1998b). When a load is applied at right angles to the insulated panel surface, the outer skins are in either tension or compression, while the core transmits the load between the skins. For example, a typical 50 mm thick PIP can span approximately 4 - 5 m, unsupported, in a ceiling situation.

Because the core of some types of insulated panel, including the EPS core of PIP, is combustible, it is possible that the core material can become involved as a fuel source for a fire. Subsection 3.3.3 of this report describes in more detail the different types of core material that are used in the manufacture of insulated panel. And even if the core of the insulated panel does not become involved in the fire, the skins can delaminate from the core material. With typical adhesives, delamination of the outer facings of the insulated panel will occur below 300 °C (Cooke, 1999) and in a series of tests conducted by the Fire Research Station, all the insulated panels that were tested, regardless of core material, delaminated 'at temperatures below 250 °C' (Lynch, 1999).

1.2 Report Objectives

This report investigates the performance of PIP, specifically the EPS core of the panel, when it is exposed to a radiant heat source.

Firstly, a review is made of the available international literature so as to provide general information about insulated panel.

Secondly, the report describes a series of experiments that were conducted for the express purpose of investigating how the combustible core of PIP would react when exposed to radiation from a metal surface at elevated temperatures. This is simulated under laboratory conditions by exposing the EPS core of PIP samples to radiation from a cylindrical radiant heat source. The experimental set-up is intended to represent a flue passing through a PIP roof or ceiling of a typical building. Analysis of the data generated by the experimental programme is also presented.

The report concludes by discussing the safety issues involved where a flue passes through a PIP building element.

2.0 LITERATURE REVIEW

Internationally, there is an ever-increasing body of literature that relates to the performance of insulated panel in fire situations.

The majority of these publications do not deal in detail with the specific subject of this report, but they do serve as useful background to the topic.

This section of the report breaks the published information into a number of separate categories which each focus on different aspects of the fire performance of insulated panel.

2.1 Fire Incidents

From the literature reviewed for this report it would appear, anecdotally, that the number of fires involving insulated panel is increasing. It is not actually possible, however, to draw such a conclusions from the data because the figures are not specific enough to indicate whether the number of fires involving insulated panel is increasing as a percentage of the total number of fires. It could simply be a case of increased reporting, or greater usage of the product. In many cases, the published literature does not identify which core material the insulated panel contained.

A recent ten year study, conducted by industrial and commercial property insurer FM Global (Battrick, 2001), shows an increase in the contribution of plastic construction materials to fire losses. The study looked at 70 large fire losses over the period 1988-97 that occurred in several countries. In all 70 fires, some type of plastic was both used in the construction of the buildings and a significant factor in the magnitude of the loss. More detailed analysis of the study shows that insulated metal panel constituted 19, or just in excess of one quarter, of the 70 incidents.

There have been a significant number of fires in the food processing sector in the United Kingdom (UK). In the period 1992-97, 39 such fires were reported to the UK Fire Protection Association (Cooke, 2001b; Day,1998) where insulated panel was

used in the construction of the premises. No less than twenty four of these fires occurred in the two-year period January 1996 to December 1997 alone.

The most well publicised fire incident in the UK involving insulated panel occurred at the premises of Sun Valley Poultry Limited in Hereford on September 1993 (*Fire Prevention*, 1995b; Harwood and Hume, 1997). The different types of insulated panel used in the construction of the building had cores of 'non-combustible mineral wool, combustible expanded polystyrene and polyurethane' (Shipp et al, 1997). In this particular fire, two fire fighters were killed as a result of the insulated panel ceiling collapsing and poor visibility (Cooke, 1997).

Following the Sun Valley fire, the British Home Office commissioned a report (Shipp et al., 1997) into the fire safety of insulated panel. The first phase of the project involved sending a questionnaire to all fire brigades in the UK requesting information on fire incidents involving insulated panel. Thirty seven brigades responded to the questionnaire, and a total of 21 fire incidents involving insulated panel were analysed. Both cold storage and food processing buildings 'are generally perceived as being of high risk' (Harwood and Hume, 1997). However, only two of the 21 incidents involved cold storage buildings, while twelve involved food processing facilities and a five more were in factory buildings. The main conclusions drawn from the 21 incidents were that:

- all the fires produced large quantities of black smoke
- firefighting could not be carried out in 8 of the buildings, and in a further three, fire fighters had to evacuate the premises
- the only fatalities occurred in the Sun Valley fire
- in all cases, occupants escaped from the building

In September 1991, a fire occurred in a chicken processing factory constructed from insulated panel, located in North Carolina. Of the 90 staff present at the time of the blaze, 25 were killed and a further 54 injured (Morgan and Shipp, 1998).

The most widely publicised fire involving PIP in New Zealand, in recent times, occurred at the Christchurch premises of Ernest Adams Limited in February 2000.

The majority of the building was constructed from PIP. One of the New Zealand Fire Service reports that summarised the investigation of the fire incident concluded that ‘the sustained elevated temperatures in the flue assembly were sufficiently high for a fire to occur in the polystyrene [core of the PIP roof panels] and that there was a sufficiently high energy release rate from the flue for this fire to be self sustaining until the fire had grown in size for its own heat release rate to be self sustaining’ (Hefford, 2000). The building was virtually totally destroyed by the fire. In addition, four fire fighters were injured in the incident. Two Fire Service personnel were injured as they exited a large roof/ceiling void where the fire initially took hold, while a further two received injuries when a section of ceiling collapsed (NZFS, 2000b). All 75 occupants of the building evacuated successfully.

2.2 Fire Fighting

Following the Ernest Adams fire in Christchurch, the New Zealand Fire Service produced a publication (NZFS, 2000a) dealing with the hazards of fires in buildings constructed from PIP. In relation to fire fighting tactics, the document recommends that personnel should not attempt fire fighting within burning PIP buildings. The bulletin goes on to recommend that rescue entry should only be attempted in extraordinary circumstances, suggesting that ‘successful rescue...is extremely unlikely’ (NZFS, 2000a).

‘Wide concern over the problems of fighting fires in buildings containing sandwich panels’ (Morgan and Shipp, 1999) prompted the Fire Research and Development Group of the British Home Office to commission a report which studied the fire fighting options for fires involving insulated panel. This was deemed necessary because ‘there [was] a clear unusual risk to fire fighters who may have to enter such a [PIP] building on fire’ (Morgan and Shipp, 1998). The majority of the Home Office report provided a summary of a workshop attended by Fire Brigade personnel, where fire fighting options were discussed. The report concluded that British fire brigades

were reluctant to adopt the defensive tactic of abandoning a building to destruction even though the dangers of fires in insulated panel buildings were now more apparent.

2.3 Fire Safety

There is an ever-increasing body of literature that deals with the issues relating to the fire safety of insulated panel, the majority originating in the UK. These publications deal with the various aspects of the panels fire safety, such as structural stability, risk assessment, fire performance, life safety, loss prevention, safe design, etc.

The evidence in the literature points to the fact that fires involving insulated panel do not pose a risk to building occupants generally (Harwood and Hume, 1997; Morgan and Shipp, 1998), but rather to those who are fighting the fire. The problems for the fire fighter include:

- recognising that insulated panel, possibly with a combustible core, is involved in the fire
- speed of development and spread of the fire
- rapidly spreading fire hidden within panels and ceiling cavities
- large quantities of thick, black smoke produced
- delamination and collapse of panel skins
- collapse of suspension systems
- difficulty of extinguishment

Dr Gordon Cooke, an international fire safety consultant and Visiting Professor, Department of Civil Engineering, City University, London, has written extensively on the fire safety issues involved with insulated panel in fires. Eurisol, the UK Mineral Wool Association, commissioned Dr Cooke's most significant publication, a report that deals thoroughly with fire safety and risk assessment (Cooke, 2000). The report comments that insulated panel that has a non-combustible mineral wool core and properly attached facings can be safely used in any relevant application, while panels with a combustible foamed plastic core risk being a fire hazard (Cherry, 2001).

The International Association of Cold Storage Contractors (IACSC) is the organisation that represents the cold storage construction industry. The membership of the European Division of the IACSC, based in the UK, consists of companies that design and/or construct cold storage buildings, as well as specifiers, suppliers and sub-contractors to the industry. The European Division of the Association published a guide (IACSC, 1999) that aims to raise the standard of design and construction in cold storage facilities, as well as introduce improvements to increase the stability of insulated panel in fire situations (Bittles, 1999, 2000).

Associated with the publication of the IACSC guide was the introduction of a “fire stable building certification scheme”. The scheme provides confirmation that the design and installation of a particular building complies with the IACSC guide. The scheme also includes a panel identification system, which allows anyone from the building occupier to fire fighters to understand where insulated panel containing combustible plastics is used and what type of material they are dealing with (*Fire Prevention*, 2000a; HO, 1999a). The overall objective of the “fire stable building certification scheme” is to improve the fire stability of insulated panel buildings.

Another important component of the IACSC guide is the recommendation to apply risk assessment techniques as part of a fire engineering study a any building as a whole (Wade and Clampett, 2000). However, Cooke contends that ‘the fire risk assessment method proposed in the IACSC guide is unsatisfactory’ (Cooke, 2001c). His concern stems from the fact that the IACSC guide proposes non-standard risk assessment techniques that do no take account of heat release, smoke production and toxic hazard.

Another issue often associated with insulated panel is that of the fire load it potentially provides. Cooke (1998b) discusses this issue, concluding that in situations of a low fire load due to building contents and thick insulated panel, the combustible insulated panel core can be in excess of half the total fire load in the building.

The literature also contains reference to the influence of the thermal insulation provided by insulated panel walls and ceiling on fire development within a compartment. Thermal inertia is calculated as the product of the thermal conductivity, the density and the specific heat of a material, in this case the core of the

insulated panel. The lower the value of the thermal inertia, the higher the insulating performance of a material, and hence the fire temperature within a compartment is maintained longer. Insulated panel has a very low thermal inertia value when compared to more conventional building materials. For example, the plasterboard lining a compartment has a thermal inertia of approximately 130×10^3 , while insulated panel lining would be correspondingly approximately $1/100^{\text{th}}$ of that value. The generally held view is that the low thermal inertia properties of insulated panel increase the speed of fire development and time to flashover, regardless of the contribution that the core of the insulated panel may, or may not, make to the fire (Butcher and Parnell, 2001). Cooke (2001b) cautions against such a simplistic conclusion, referring to testing that illustrated the complexities of predicting the time to flashover.

2.4 Fire Testing

An assessment of the performance of different products is made by means of fire tests. Typically, products are given a classification based on the outcome of such testing. This classification can then be used by Regulatory Authorities as a means of maintaining safety levels (Smith et al., 1999).

A considerable amount of work has been done internationally to develop fire tests that give an accurate representation of the performance of insulated panel in real fire situations. The general concern is that some of the current small-scale test procedures do not adequately predict the behaviour of insulated panel in fires (Cooke, 1987; Parlor, 2000).

2.4.1 Insurance Industry

The insurance industry, in both the UK and the United States, has been active in the development of fire tests that are relevant to insulated panel. For example, the US-based insurer, Factory Mutual, has developed a number of both large and small-scale tests that provide a means of classifying different plastic building materials (FMEC, 1981). Similarly, the Loss Prevention Council (LPC) in the UK has developed large-scale test methods for evaluating performance of insulated panel. Loss Prevention Standard LPS 1181 (LPC, 1996), a large-scale reaction to fire test, 'now forms the cornerstone of UK insurance industry led requirements' (Day, 1998). The LPC has also produced a Design Guide for the Fire Protection of Buildings (FPA, 1999), which provides guidance on insulated panel installation. The LPC has also published a code of practise (LPC, 1999) which deals with fire protection in the food and drink industry. In addition, the LPC has produced two Loss Prevention Standards that deal exclusively with the fire performance of insulated panel, namely LPS 1208 (LPC, 1995) and LPS 1220 (LPC, 1997).

2.4.2 ISO 9705 Room/Corner Test

In 1993, the International Organisation for Standardisation (ISO) published ISO 9705: Fire Tests – Full-scale room test for surface products (ISO, 1993). This test method is commonly referred to as the Room/Corner Test. The Room/Corner Test is a large-scale reaction to fire test method that measures the Heat Release Rate (HRR) and Smoke Production Rate (SPR) of the product being tested (Sundström et al., 1998). The product lines three walls and the ceiling of a compartment that measures 2.4 m wide, 3.6 m long and 2.4 m high, as shown in Figure 2.4.2.1:

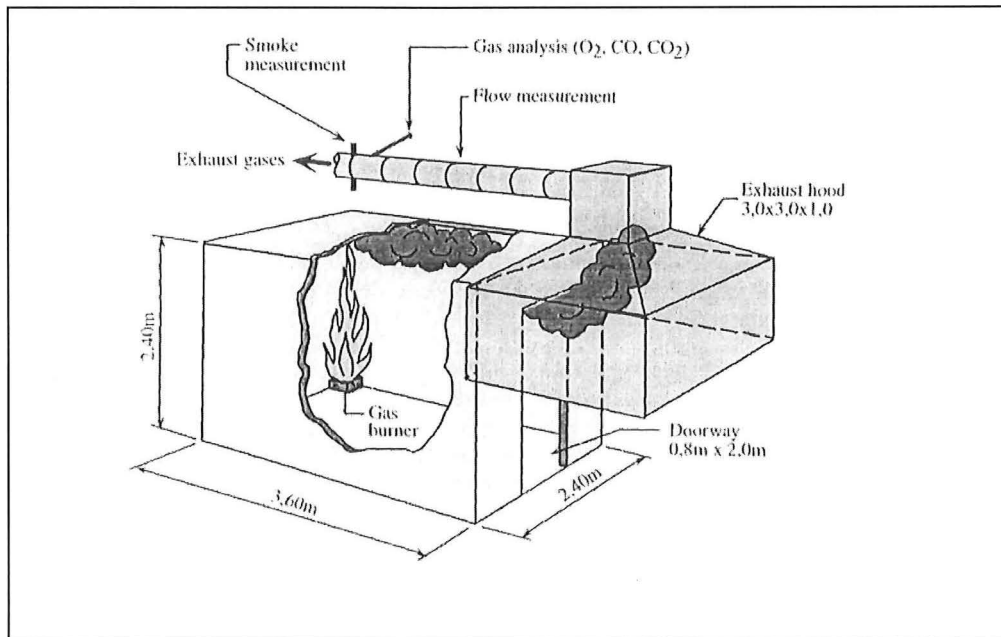


Figure 2.4.2.1 – The ISO 9705 Room/Corner Test

(Reproduced from Sundström et al., 1998)

A gas burner is placed in one corner of the room. The burner output is 100 kW for the first 10 minutes of the test and 300 kW for the second 10-minute period. The test is terminated after 20 minutes, or when flashover occurs. Flashover is defined as being when the total HRR reaches 1000 kW.

The HRR rate that results from each test gives rise to the FIGRA index, or Fire Growth Rate index. The 'FIGRA [index]' is based on the fact that a small fire is less hazardous than a large fire and that a rapidly growing fire is more dangerous than a slowly growing fire' (Sundström and Christian, 2001). It is calculated by dividing the peak HRR of the fire excluding the contribution from the ignition source by the time at which this occurs. The units for the FIGRA index are kW/s. For the test to be terminated at flashover, the maximum HRR from the product only, i.e. less either 100 kW or 300 kW for the burner, can be either 900 kW or 700 kW. This depends whether the peak occurs during the first or second 10-minute period of the test. Figure 2.4.2.2 shows examples of this calculation:

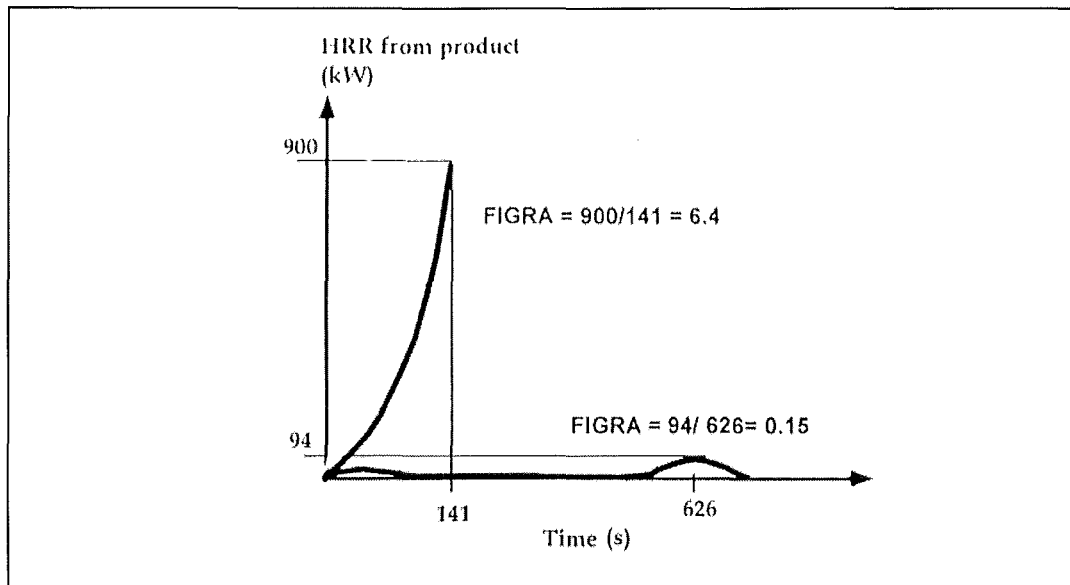


Figure 2.4.2.2 – Calculation of the FIGRA Index

(Reproduced from Sundström et al., 1998)

The SPR is represented as the SMOGRA index, or Smoke Growth Rate index. This index is calculated as being the 60-second average of peak SPR divided by the time at which the peak occurs. The resulting value is multiplied by 1000 to make it comparable in magnitude to the FIGRA index, and has units of m^2/s^2 .

In 1998, the Swedish National Testing and Research Institute published a report that ranked the fire performance of various products when tested to ISO 9705 (Sundström et al., 1998), including PIP. Of the 30 products tested, PIP was ranked 15th best with a FIGRA index of 0.72 kW/s, and a SMOGRA index of 7.0 m^2/s^2 . Flashover occurred during the second 10-minute period when the burner intensity was 300 kW.

Parlor (2000) discusses the comparison between various types of insulated panel that is summarised in the European Commission document RG N130 – The FIGRA indices for 59 building products in the ISO Room/Corner. Insulated panel with a mineral wool core is best with a ranking of 10th, PIP is 22nd and polyurethane panel is 34th.

2.4.3 Modified ISO 9705 Test

Although the ISO 9705 Room/Corner Test has wide acceptance, it does not test insulated panel under true end-use conditions (Johansson and Van Hees, 2000). The Swedish National Testing and Research Institute undertook a project that aimed to develop a full-scale test procedure which accurately reflected as-built construction but at the same time retained the philosophy of the ISO 9705 test method (Van Hees and Johansson, 2001a, 2001b). The purpose of exploring more realistic alternatives was in an attempt to assess the true significance of jointing systems and construction detailing.

A method was developed which tested insulated panel in a free-standing arrangement, rather than as a lining of a compartment, while maintaining the same dimensions. The main issue of realism associated with the ISO 9705 method is that it is not possible to apply fixings, etc., to the external face of the insulated panel that forms the lining of the test compartment. Essentially, the test room was built under a large calorimeter, rather than having an exhaust hood at the doorway of the ISO 9705 compartment, shown in Figure 2.4.2.1. The modified method also allows the option of supporting the insulated panel.

Insulated panel with four different core materials was tested as part of the project. For the stone wool panel, there was no significant difference between the ISO 9705 and modified method. For PIP, performance improved, while for polyurethane and polyisocyanurate, the performance was worse.

The overall conclusions from the project were that:

- it is important with insulated panel to carry out reaction to fire tests of realistic end-use conditions
- joint detailing is an important factor in the fire behaviour of insulated panel

Correspondingly, ISO has developed test methods for free-standing insulated panel (ISO, 1999a, 1999b).

2.4.4 European Fire Classes - Euroclasses

The purpose for harmonising the testing and classification of building products within the European Union is so that the 15 member states can have free trade for building products. Safety of building products in case of fire is one element of this harmonisation process, and has given rise to the new European Fire Classes, or Euroclasses, system of classification.

Sundström and Christian (2001) provide a thorough explanation of the Euroclassess system that was published by the Commission of the European Communities (EC, 2000) as Commission Decision 2000/147/EC. The Euroclassess system is a reaction to fire classification system with seven classes, namely A1, A2, B, C, D, E, and F, with Class A1 being the highest level of performance that corresponds to the least combustible type of material (Smith, 2001). For each of these classes, specific tests are required and certain performance criteria achieved.

The most important test method for lining materials is called the Single Burning Item (the SBI), as specified in standard prEN 13823 (CEN, 2000). The SBI is an intermediate scale test where two samples of the product, one 0.5 m wide by 1.5 m high and the other 1.0 m wide also by 1.5 m high, are built as a corner. Figure 2.4.4.1

shows the SBI test configuration:

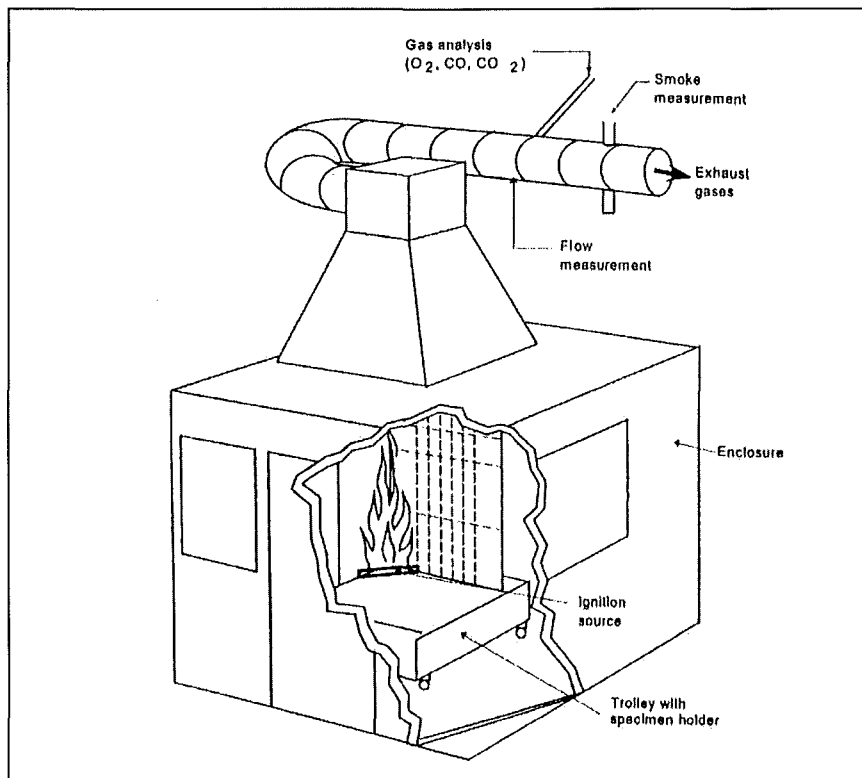


Figure 2.4.4.1 – Single Burning Item (SBI)

(Reproduced from van Mierlo and Sette, 2001)

A 30 kW burner is placed in the corner and burning behaviour monitored for 20 minutes, with HRR and SPR measured. The Fire Growth Rate index, the FIGRA(SBI), differs from that for the ISO 9705 test in that it is the maximum or total value of HRR in the 600 second test period - the SMOGRA(SBI) index has the same difference. With the results from Room/Corner tests being used as the reference, a comparison between SBI and ISO 9705 results was done by Sundström et al. (1998) that showed a good correlation between product rank and FIGRA indices. On this basis, the FIGRA(SBI) and SMOGRA(SBI) indices were used to derive the new Euroclasses.

Van Hees and Johansson (2001a) showed, however, that for insulated panel, the SBI results did not correlate very well with the full-scale results, and 'the products behave[d] in most cases much better in the intermediate scale SBI test' (Johansson and Van Hees, 2000).

In work done by the Building Research Establishment, 'financial and time-scale limitations' (BRE, 2001; Day, 2001) meant that a corner test configuration was used to evaluate the fire performance of different insulated panel types, rather than a full-scale room test. The test arrangement is shown in Figure 2.4.4.2, with insulated panel samples 3.0 m high and 2.0 m and 1.0 m wide respectively, as well as a ceiling:

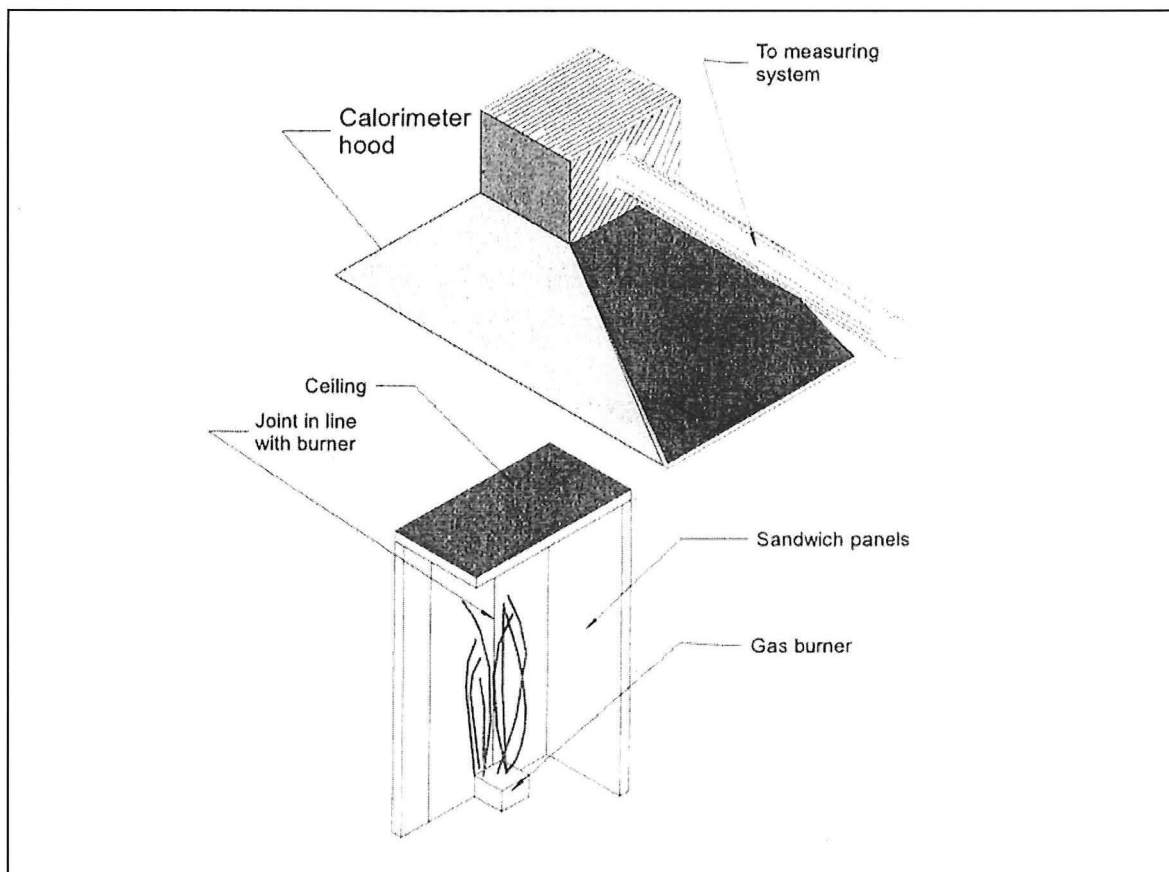


Figure 2.4.4.2 – Loss Prevention Council Corner Test

(Reproduced from BRE, 2001)

As well as being on a larger scale than the SBI test, the heat output from the burner was higher, and the duration of the test was longer. For the first 5 min of the test, the

heat output is 50 kW. It then steps up to 100 kW for 10 min, 300 kW for 10 min and finally up to 500 kW for the final 10 min, a total of 35 min.

3.0 EXPANDED POLYSTYRENE INSULATED PANEL

3.1 Historical Usage of PIP

PIP has been manufactured in New Zealand for over thirty years. Initially used in the primary meat industry for freezing works, the product now has wide usage as an insulated building material in a variety of applications. Some of the typical uses in the New Zealand market currently are:

- large industrial coldstores operating at temperatures as low as -40 °C
- coolrooms in supermarkets, restaurants, etc.
- winery processing buildings
- chicken rearing sheds
- cow milking sheds
- residential conservatory roofing
- food processing factories
- external cladding and façades on commercial buildings
- roofing for industrial and commercial buildings
- portable and relocatable buildings

In excess of 750,000 m² of PIP is manufactured in New Zealand per annum, with a significant portion consumed for the national market and the balance exported.

All insulated panel made in New Zealand currently has an EPS core, with all manufacturers having vertically integrated plants that also manufacture their own

EPS. A small amount of insulated panel with alternative core materials is indented into the country.

3.2 Manufacture of PIP

The three basic components used in the manufacture of PIP are the EPS insulating core, metal skins and an adhesive that bonds the metal skin to the core.

The EPS core of PIP is typically class S, commonly known as S-grade, in accordance with the Australian standard for the manufacture of rigid cellular polystyrene, AS 1366.3 (SA, 1992). EPS used as the core of PIP has a nominal density of 16 kg/m³ and a typical thickness of 50–300 mm.

By far the most commonly used metal skin is pre-painted mild steel. The steel typically has a nominal Base Metal Thickness of 0.59mm, and has a protective coating of either zinc, also known as galvanising, or a mix of zinc and aluminium. If correctly designed, detailed, installed and maintained, either of these materials will satisfy the regulatory requirement for a fifteen year durability for external cladding materials, and where required can achieve a fifty year durability period.

A typical coil of the pre-painted steel product used in the manufacture of PIP weighs up to 5 tonne, which gives a yield of approximately 800–900 m² of the finished insulated panel. Domestic suppliers manufacture the majority of the steel coil used to manufacture PIP in New Zealand, although a reasonable proportion is sourced internationally.

Small quantities of stainless steel and aluminium are also used, but this would be the exception, and has to be imported.

The adhesive used to bond the metal skins to the EPS core is typically a two-part, thermosetting polyurethane. When adhered correctly, the shear strength of the glue-to-core interface is stronger than the shear strength within the EPS core material. This

effect is clearly illustrated by quality control testing during manufacture, where stripping metal skins away from the core leaves a layer of EPS beads adhered to the metal skin. The adhesives are either sourced from New Zealand manufacturers or indented.

The actual manufacture of the PIP is a mechanised process which bonds the metal skins to both sides of the sheets of EPS core material. Sheets of EPS, cut to the required thickness, are fed end-on-end into the laminating machine between coils metal. As the coils move through the process, they are progressively roll-formed to achieve the required surface profile and edge jointing detail. A typical coil of metal has an initial width of 1260 mm that results in an insulated panel of 1200 mm module width. Concurrently, glue is applied and the metal skin and EPS core are bonded together under pressure. The final stage of this continuous process is to cut the finished panels to their required length. A finished panel length of approximately 25-30 m is the typical maximum that can be handled either by road freight or by craneage on construction sites.

3.3 EPS Core of PIP

3.3.1 Material Description

Plastics are classed as synthetic polymers and are organic compounds of high molecular weight, made from repeated units of lesser molecular weight called monomers (Hilado, 1990). Polystyrene is manufactured by the polymerisation of the styrene monomer, shown in Figure 3.3.1, and is a derivative of ethylene and benzene:

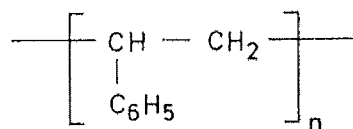


Figure 3.3.1 – Styrene Monomer

(Reproduced from Troitzsch, 1990)

Foamed, or cellular, plastics consist of materials that have gas more or less uniformly distributed throughout the base synthetic polymer.

It is theoretically possible to produce foams from virtually any plastic, although only a limited number have gained commercial significance. Generically, there are three distinctive types of foamed plastics, namely thermoplastic, thermosetting and elastomeric foams, depending on which polymer they are derived from (Troitzsch, 1990).

Thermoplastics consist of threadlike cross-linked macromolecules that soften when heated and then harden again when they cool. This process of physical change can be repeated indefinitely so long as the chemical changes associated with excessive temperature do not occur.

Thermosets are rigid and cannot be plastically formed at elevated temperatures. Their rigidity is due to an irreversible curing reaction that forms a three dimensional cross-linked chemical structure.

Elastomers are flexible foams that have an open cell structure. This open cell structure gives elastomers poor thermal insulation properties but excellent elongation.

In contrast, thermoplastic and thermosetting foams have a closed cell structure that gives them low thermal conductivity and hence they are very effective insulating materials.

The EPS core of PIP is a rigid cellular (foamed) thermoplastic.

The glues that are used to adhere the metal skins of PIP to the EPS core are rigid thermosetting polyurethane foams.

3.3.2 Manufacture

As stated in section 3.2, EPS in New Zealand is produced to an Australian manufacturing standard, AS 1366.3, which stipulates performance requirements for six physical properties to meet each different class or grade (SA, 1992).

The polymerisation process by which EPS is manufactured produces translucent spherical beads that are approximately 0.5-1.0 mm in diameter, which is about the size of sugar granules. During this manufacturing process, a low boiling point hydrocarbon, pentane, called a “blowing” agent, is introduced into the beads.

The pentane is required for bead expansion at a subsequent stage of the production process (PINZb). All the EPS bead used in the New Zealand market is imported from manufacturers in either Australia or Asia.

The EPS manufacturing process has three primary stages. In the first stage, the polystyrene beads are expanded to form a hollow sphere that is approximately 40-50 times its original volume. Taking advantage of the encapsulated pentane, the beads are heated to approximately 100 °C with steam in an enclosed vessel called a pre-expander, while being stirred constantly. At this stage of the manufacturing process, the density of the EPS is controlled. Generally, for the same raw bead, the longer the bead is pre-expanded, the larger the diameter of the expanded bead and the lower the EPS density, and vice versa. The larger the expanded bead diameter, the less the thickness of the solid polystyrene wall of the spherical bead and hence the less solid polystyrene per unit volume.

The pre-expanded beads are cooled and dried in a fluidised bed drier, and then moved either pneumatically or mechanically to storage silos for maturing.

The maturing phase is the second stage of the process. It involves holding the pre-expanded beads in silos for approximately 24 hours so the beads can stabilise. The core of the pre-expanded beads is partially under vacuum, and during the ageing

process, air diffuses slowly through the polystyrene wall of the bead, replacing the majority of the pentane blowing agent and reaching equilibrium.

The third and final primary stage in the production of EPS is the moulding stage. Matured, expanded beads are pumped into a mould, totally filling it. In the mould, steam is introduced, softening the beads and they start to expand further. However, the constraining effect of the mould causes the softened beads to fuse together under pressure when the correct temperature is reached. The fused blocks are allowed to cool under vacuum, which removes moisture from the blocks. The moulded blocks are then ejected from the mould, and the cycle is repeated. A further portion of the residual pentane blowing agent is released during the moulding stage.

In relation to the manufacture of PIP, EPS is block moulded, i.e. blocks from 3600 - 5400 mm long, 1200 mm wide and 600 mm deep.

The first stage of post-production, or secondary processing, is kiln drying. The moulded blocks are dried at a temperature of approximately 70 °C in an enclosed kiln for 3-7 days. During the kiln drying process, all moisture is driven out of the blocks, the blocks shrink to a dimensionally stable size, and the final residue of pentane is removed from the cellular beads.

The final secondary process, required prior to PIP manufacture, is for the blocks to be cut into sheets. The typical cutting process is to use small diameter hot wire cutters. High resistance metal wires are spaced over the 600 mm depth of the blocks from side-to-side and are heated up by applying an electrical current. The heated wires, stretched over the 1200 mm block width, are then drawn along the length of the block, thus producing sheets of the required thickness.

If moisture is not removed from the EPS blocks by kiln drying, the heated wire cutters cool down as they pass along the length of the blocks. This causes the wires to drag, resulting in a rough, uneven surface. Such a finish on the EPS sheets leads to PIP with noticeable surface imperfections. Tight control of sheet thickness in particular, to avoid steps at sheet butt joints, is crucial to being able to produce good quality PIP.

If any residual pentane is not removed from the EPS blocks by kiln drying, there is a risk that the blowing agent gas could ignite during hot wire cutting.

3.3.3 Alternative Core Materials

All insulated panel currently manufactured in New Zealand has an EPS core. Internationally, however, there is a range of other insulating core materials, each with their own properties. Cooke (1999b) and Day (2001) give a summary of the alternatives.

The alternative core material that most closely resembles EPS is extruded polystyrene foam (XPS). XPS is formed by melting solid polystyrene, additives and a blowing agent under controlled high temperature and pressure. The hot viscous liquid is then extruded through a die and expands, giving it uniformly small closed cells and a smooth outer skin. To the naked eye the material appears to have a homogeneous consistency which differs from the visibly cellular structure of EPS. XPS has similar fire performance to that of EPS.

Rigid polyurethane foam (PU) is another core material used in the manufacture of insulated panel. PU is produced from the reaction of isocyanates and alcohol (Troitzsch, 1990) and subsequent polymerisation. Rigid PU foam is typically manufactured to a density of approximately 30 kg/m^3 , using carbon dioxide as a blowing agent, and has approximately 5% of cells open. It is resistant to temperatures up to 120°C and degradation by the process of depolycondensation commences at 220°C , forming the original isocyanate monomer and alcohol (Troitzsch, 1990). The combustible gases which form can be ignited at approximately 300°C and will self-ignite at approximately 400°C (Hilado, 1990). When PU burns, it does so with a light yellow luminous flame.

The next type of insulant used in the production of sandwich panel is a hybrid of polyurethane called polyisocyanurate (PIR). PIR is formed from the same initial materials as PU, except that an excess of isocyanate is used. A catalytic trimerisation

reaction of the isocyanate occurs, forming isocyanurate rings. The polymerisation process forms extremely stable three-dimensional PIR networks that have increased rigidity and thermal stability, as well as reduced flammability when compared to PU (Troitzsch, 1990). The temperature resistance of PIR is 20-50 °C higher than for PU. Only a slight amount of depolycondensation occurs for PIR, in comparison to PU, which produces only small quantities of combustible gases and low levels of smoke production during combustion. PIR extinguishes away from an ignition source, forming a carbonaceous char layer that insulates underlying foam.

Yet another material used, as a core for insulated panel, is phenolic (PF) foam. This material is hard and brittle and is classed as being mixed cell because it is a minimum of 25% open cell. Standard densities for PF range from 40 to 100 kg/m³. The prolonged level of temperature resistance is 130 °C, but the material can accommodate short exposure to temperatures up to 250 °C. At temperatures of 270 °C and above, small quantities of volatile gases are produced by means of decomposition. These combustible gases burn for a few seconds. Above 400 °C, PF will continue to incandesce, or glow, but not flame or self-ignite. When an ignition source is removed, the PF foam will continue to smoulder, but very little smoke is produced, and a stable char is left (Troitzsch, 1990).

There are two other core materials used commercially, neither of which is a foamed plastic. The first of these is mineral wool. Mineral wool is made from inorganic fibres that are non-combustible (Cooke, 1998b). Two different types of fibres can be used to make mineral wool. Glass wool is produced by melting silica sand in a large vessel and then spinning it into woolly filaments that are bound together into sheet form with low-calorific binders. The fiberising process for rock wool is similar, with the raw material being basaltic rock. One difference in the process is that when the volcanic rock is turned into fibres, pieces of solid rock, called shots, are also included. These fragments add significantly to the weight of the sheet, without contributing to the thermal performance (British Gypsum-Isover, 1998). When used as insulated panel core, the fibres are perpendicular to the skin of the panel, which gives the optimal strength to the panel (Cooke, 2000). Mineral wool has one drawback in coolstore construction in that it is not very thermally efficient.

The second non-foam core material used in the manufacture of insulated panel is called cellular glass, or foamed glass. This product is an all-glass material made from alumino-silicate and has a closed cell structure. It is totally inorganic and because it does not contain any binders or fillers, it is non-combustible and does not produce any toxic fumes when heated (PCC, 1998). The material has an upper service temperature limit of approximately 500 °C, and is impermeable to water vapour.

3.4 Combustion of PIP

The EPS core, and to a lesser extent the polyurethane adhesives and the paint coatings on the metal skins, are the combustible components of PIP. Only the combustibility of EPS is discussed in this report, because it is present in much larger quantities than either of the other two combustible components.

3.4.1 Burning Behaviour

When heat is applied to a solid polymeric material, the material undergoes both physical and chemical changes. The physical changes are termed thermal degradation, while of the chemical changes are called thermal decomposition.

In very general and idealised terms, the thermal degradation of a thermoplastic has a number of stages, as illustrated in Figure 3.4.1.1:

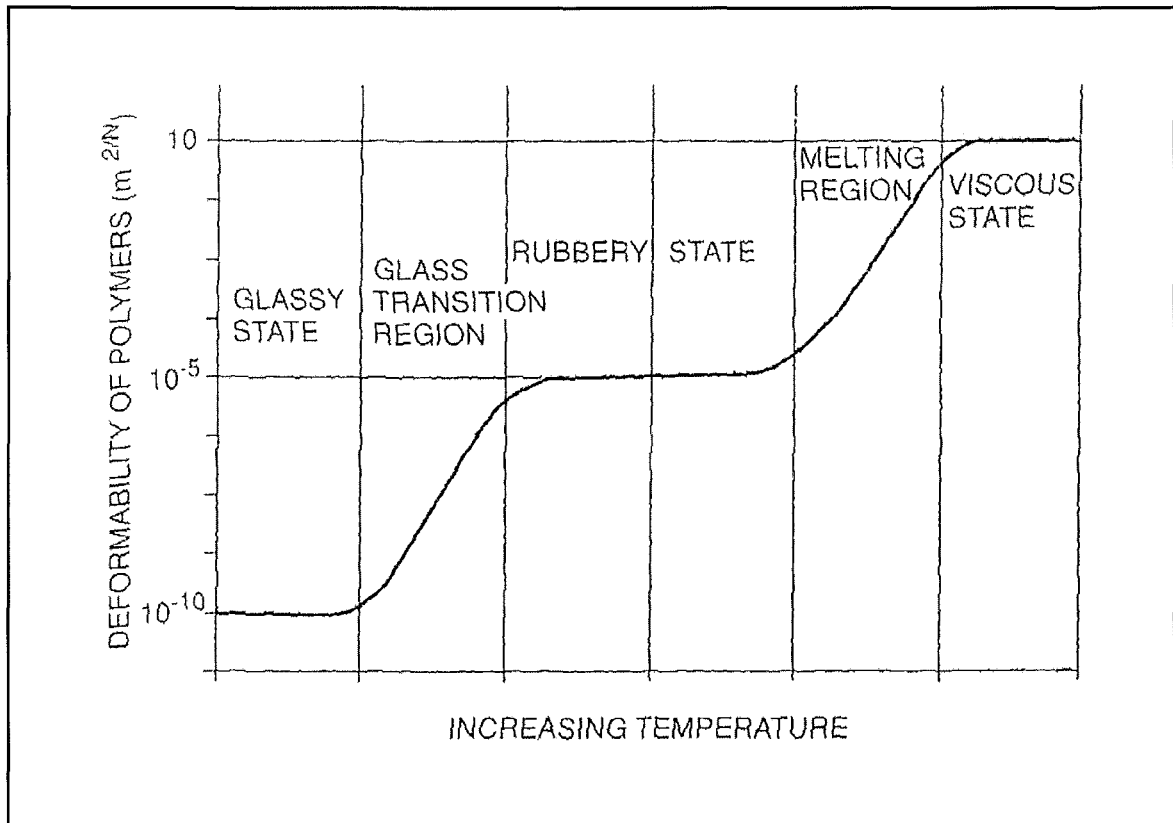


Figure 3.4.1.1 – Idealised View of Thermal Degradation of Thermoplastic

(Reproduced from Beyler and Hirschler, 1995)

When increasing temperature is applied to a thermoplastic material, it will initially go through a transition from a solid, or glassy, state to a soft, or rubbery, state. With further increase in exposure temperature, the thermoplastic goes through a melting transition to a viscous state.

EPS is resistant to short term temperatures of 90 °C and long term temperatures of 80 °C. Above these temperatures, EPS will soften, until at approximately 150 °C it will begin to shrink and return to its original density as a solid polystyrene. Continued heating will melt the EPS to a liquid and then gas form above 200 °C. Such gas can be ignited at temperatures between 360 and 380 °C, and self-ignition occurs at approximately 500 °C.

Also, EPS has a heat of combustion of approximately 40 – 45 MJ/kg (Troitzsch, 1990; PINZa). In quoting a value of heat of combustion for EPS, it is important to remember that the material is only 2-3% polystyrene by volume. For example, a 100

mm thick PIP ceiling panel will contribute approximately 70 MJ/m² fire load within a building.

During the process of thermal degradation, depolymerisation of the polystyrene occurs, forming mainly monomers, dimers and trimers.

With respect to combustion, the chemical changes associated with thermal decomposition are important. Chemical decomposition of the solid polymeric material produces gaseous vapours, which react with the oxygen in the air above the polymer to generate heat, i.e. burn. For the process to be self-sustaining, the burning gases must feedback sufficient heat to produce more fuel vapours. A continuous feedback loop is created which results in the solid polymer continuing to burn as shown in Figure 3.4.1.2:

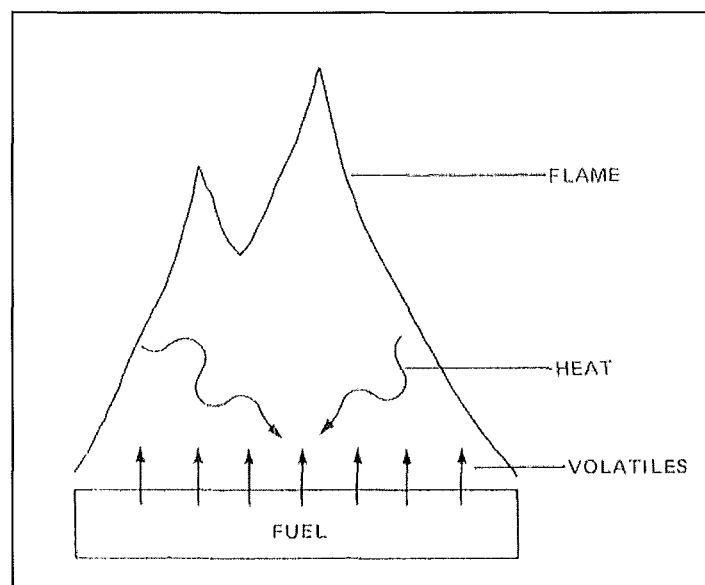


Figure 3.4.1.2 – Energy Feedback Loop Required for Sustained Burning

(Reproduced from Beyler and Hirschler, 1995)

3.4.2 Flame Retardants

Currently in New Zealand, all EPS that is used in the manufacture of PIP has flame retardant chemicals added.

The reason for adding flame retardants to plastic materials is to try and reduce flammability (FMEC, 1981). In general terms, flame retardance involves disrupting the burning process at one or more stages (Hilado, 1990). The interference of the flame retardant may occur during heating, decomposition, ignition or flame spread. Flame retardants can act chemically and/or physically in any phase (Troitzsch, 1990). The inhibiting, or even suppression, of combustion with flame retardants is a complex process where many stages occur simultaneously, albeit with a dominant reaction. An example would be a dominant endothermic reaction where dilution of ignitable gases occurs because of the generation of inert gases.

The most effective flame retardants are considered to be those that act chemically, rather than physically (Troitzsch, 1990), and the interference of the combustion process occurs in either the gas or solid phase.

In relation to the EPS core of PIP, flame retardants act chemically in the gas phase.

In the gas phase, the mechanism of combustion that forms radicals is interrupted by the flame retardant. The exothermic, or heat generating, processes of combustion are stopped, cooling occurs and the production of flammable gases is reduced or completely suppressed.

The distinction between reactive and additive flame retardants must also be made. Reactive flame retardants are built chemically into the polymer molecule, while additive ones are incorporated into the plastic, most frequently following polymerisation.

Additive flame retardants are used most especially in thermoplastics such as EPS, the most important of which are halogen-containing.

Halogen-containing flame retardants work by interfering with the radical chain mechanism, that occurs as part of the combustion process, in the gas phase. High energy radicals, OH and H , are formed by chain branching as shown in Eq. 3.4.2.1 and Eq. 3.4.2.2:



The halogen-containing flame retardant initially breaks down as shown in Eq. 3.4.2.3:



The halogen radical, denoted by symbol X , then reacts with hydrocarbon, RH , to form the hydrogen halide, as indicated in Eq. 3.4.2.4:



The resulting hydrogen halide, HX , now interferes with the radical chain mechanism by reacting with the OH and H radicals, as shown in Eq. 3.4.2.5 and Eq. 3.4.2.6:



Eq. 3.4.2.5 and Eq. 3.4.2.6 show how the high-energy H and OH radicals are removed when they react with the hydrogen halide, HX . These reactions prevent the H and OH radicals reacting with the fuel compound. The simplistic chemical process indicated by these six equations also shows that the hydrogen halide, HX , is the important reagent in the flame retarding process (Troitzsch, 1990).

There are also physical mechanisms involved in the flame retardant effect of halogen-containing substances. Not only does the non-flammable *HX* gas dilute the flammable gases present, but it also forms a non-combustible protective layer on the condensed phase below the flame zone thus providing a shield to the oxygen and radiant heat.

It is possible for flame retardants to have a negative impact on the desirable properties of the plastic. The ideal flame retardant would have the following characteristics:

- easy to incorporate into the plastic
- be compatible with the plastic
- not alter the mechanical properties of the plastic
- be colourless
- exhibit good stability in UV and light
- be resistant to ageing
- be insoluble
- match the decomposition temperature of the plastic by taking effect below the decomposition temperature of the plastic and continuing over the whole decomposition temperature range
- not cause corrosion
- temperature resistant
- effective in small amounts
- odourless
- have no harmful physiological effects
- emit low levels of smoke and toxic gases
- be cheap

It is necessary to trade-off between a decrease in the beneficial properties of the original plastic, and the effectiveness of the flame retardant. Ongoing work continues to develop the ideal flame retardant.

For EPS, bromine-containing flame retardants are used - specifically, a brominated cycloaliphatic hydrocarbon called hexabromocyclododecane (*HBCD*) is used, with a concentration of less than 1% by weight (BASF, 2001).

Considering the four possible halogen-containing flame retardants, only iodine is potentially more effective than bromine. However, iodine-based flame retardants do not actually interfere with the combustion process at the right stage, nor does its by-product have adequate thermal stability.

A number of factors make bromine an effective flame retardant. Weak chemical bonding associated with Eq. 3.4.2.3 makes the bromine available to effectively interfere with the combustion process at a more favourable point of the reaction. The hydrogen halide, *HBr*, is liberated over a narrow temperature range corresponding to the flame temperature, thus being present in high concentrations in the flame zone. Bromine is used in lower concentrations, thus having less effect on the properties of the EPS. Also, the bromine can be readily incorporated as an additive, and it does not bleed.

On the other side of the ledger, bromine-containing flame retardants have poor stability in light and are more expensive.

When added to EPS, flame retardants raise the ignition threshold when compared to untreated material. Flame retardants do not ensure non-combustibility of EPS, however. If EPS is exposed to sufficient heat, it will burn.

3.4.3 Smoke Production

During the combustion process, both smoke and toxic gases are produced. Smoke is a combination of the solid and liquid particle products of combustion, but should not be confused with the gases that are also produced. The effects of the smoke produced by a fire depend on both the quantity and its properties (Mulholland, 1995). Smoke is dangerous in fire situations because it affects visibility. In an egress route of a building for example, the denser the smoke and the more radiant heat it is giving off, the less likely people are to move through the smoke, although this can be offset by the persons familiarity with the surroundings (Bryan, 1995). Sufficient smoke can cause disorientation of building occupants in a fire and can also result in panic and

irrational behaviour. It is rare though for the death in a fire to occur as a primary result of the smoke. It is far more likely that toxic gases, lack of oxygen or heat itself will cause death in a fire situation.

Smoke results from in complete combustion and consists of a conglomeration of liquid and solid particles that vary in diameter from 0.002 to 0.5 μm . The liquid particles are droplets of the liquid products of pyrolysis, their partially oxidised derivatives and water. The solid particles are carbonaceous, i.e. carbon flakes, soot and ash, sublimed pyrolysis products and oxides of inorganic compounds (Troitzsch, 1990).

The availability of oxygen can have a marked effect on the level of smoke generated in a fire (Troitzsch, 1990; Tewarson, 1995). In the early stages of a fire, there is typically sufficient oxygen for efficient or complete combustion to occur. Under these conditions, the least amount of smoke is generated. The fire is described as being well-ventilated at this stage. As the fire develops and grows, there is often insufficient oxygen available for complete combustion of the flammable vapours. At this stage the fire is described as being ventilation-controlled, with a corresponding increase in the amount of smoke generated.

Thermoplastic materials like EPS primarily decompose to aromatic hydrocarbons in the gas phase that in turn give rise to large amounts of soot (Troitzsch, 1990). This is borne out by reports of specific fire incidents involving PIP, such as the Ernest Adams fire (Hefford, 2000).

The test method most commonly used in New Zealand to quantify smoke production for building materials is the joint Australian/New Zealand Standard AS/NZS 1530.3 (SA/SNZ, 1999). Radiant heat is applied to the specimens. One part of the procedure measures the optical density of the smoke that is collected in an exhaust hood. The greater the optical density, the denser the smoke and the greater the volume of smoke produced. A mean optical density of less than 0.0082 m^{-1} corresponds to a Smoke Developed Index (SDI) of 0, while a value of 4.20 m^{-1} or more has a SDI of 10. Generic results for EPS give a result for the SDI of 5, on a scale of 1 – 10. As a comparison, radiata pine has a corresponding SDI of 3 (PINZa).

3.4.4 Toxicity

The two major narcotic gases produced in fires are carbon monoxide (*CO*) and hydrogen cyanide (*HCN*). *CO* is always present to some extent in any fire, regardless of fuels, the stage of the fire or the type of fire. There is therefore always some risk in a fire of narcosis from *CO*. On the other hand, *HCN* can only be produced when nitrogen (*N*) is a chemical constituent in the materials involved in the fire. It should be noted that EPS does not have any nitrogen in its chemical structure. In addition, very high concentrations of carbon dioxide (*CO*₂), i.e. above 5%, and low oxygen levels, i.e. less than 15%, can also have narcotic effects (Purser, 1995).

The issue of the toxicity of burning EPS is a subject that has attracted much comment. When tested in accordance with the German Standards Organisation, or Deutsches Institut für Normung (DIN), test method DIN 53 436, burning of EPS produces *CO*, styrene monomer, other aromatics and *HBr* in measurable quantities. Of these substances, only *CO* is in significant quantities in terms of toxicity. However, the fumes produced from burning EPS represent no greater toxic risk than fumes from natural materials, such as wood, cork or wool (BASF, 2001b). The flame retardant additives in EPS will also produce toxic polybrominated dibenzodioxins (*PBDD*) and dibenzofurans (*PBDF*). Studies conducted in Germany have shown that these toxic substances are only produced in negligibly small quantities (BASF, 2001b; BIER, 1994).

3.5 New Zealand Building Code Requirements

Under the regulatory framework for the construction of buildings in New Zealand, the New Zealand Building Code (NZBC) specifies mandatory performance criteria that must be met. In relation to fire safety in buildings, the relevant Clauses of the NZBC are:

- C1 – Outbreak of Fire
- C2 – Means of Escape
- C3 – Spread of Fire

- C4 – Structural Stability During Fire

The Building Industry Authority (BIA) provides non-mandatory guidance documents, called Acceptable Solutions, which offer one method of achieving compliance with NZBC Clauses. With respect to fire safety in buildings, this guidance document is Acceptable Solution C/AS1 (C/AS1).

Acceptable Solutions are just one way of meeting NZBC requirements. The building designer is at all times free to develop an Alternative Solution as a means of achieving NZBC compliance.

In C/AS1, there are a number of requirements that relate to the use of PIP as a building material. Some of these requirements relate to any building material, but some are specific to products that contain foamed plastics.

3.5.1 Control of Internal Fire and Smoke Spread

Part 6 of Acceptable Solution C/AS1 has specific requirements to protect foamed plastics from ignition when used as internal lining materials. These requirements are

summarised within C/AS1 as Table 6.3, which is reproduced herein as Table 3.5.1.1:

Application	Required properties (see Note)		
	Purpose Groups SR, SA, SH	Purpose Groups SC, SD	Purpose Groups CS, CL, CO, CM, WL, WM, WH, WF, IA, ID
Sleeping areas	fb + p	fb + p	n/a
Exitways unsprinklered	fb + p	n/a	fb + p
Exitways sprinklered	fb + p	fb + p	fb + p
Non-sleeping <i>occupied spaces</i> unsprinklered	fb + p	n/a	fb + p
Non-sleeping <i>occupied spaces</i> sprinklered	sf + p	fb + p	sf + p
<i>Concealed spaces</i>	p	fb + p	p
Key: p <i>foamed plastics</i> shall comply with the flame propagation criteria as specified in AS 1366 for the type of material being used. sf <i>surface finish</i> shall comply with Paragraph 6.20.3 for <i>spread of flame index (SFI)</i> and <i>smoke developed index (SDI)</i> . fb <i>flame barrier</i> complying with Appendix C Paragraph C10.1.			

Table 3.5.1.1 – Foamed Plastics – Protection from Ignition

(Reproduced from BIA, 2001)

For EPS to meet the flame propagation criteria referred to in Table 3.5.1.1, the material must pass the test method AS 2122.1 (SA, 1993). The flame retardant additives in EPS allow the material to meet the flame propagation requirements of C/AS1.

The SFI and SDI requirements for the surface finish of the foamed plastic, which for PIP is the painted metal skin, are assessed in accordance with AS 1530.3 (refer to subsection 3.4.4).

Generally, PIP used in New Zealand will meet these requirements.

For PIP to meet the flame barrier requirements, the product is tested for 10 minutes in accordance with AS 1530.4 (SA, 1997), the standard fire resistance test method. The furnace temperature can be calculated from Eq. 3.5.1.1:

$$T_t - T_0 = 345 \log_{10}(8t + 1) \quad (3.5.1.1) \text{ (SA, 1997)}$$

where

T_t = furnace temperature at time t , in degrees Celsius

T_0 = initial furnace temperature, in degrees Celsius, not less than 10 °C nor more than 40 °C

t = time into the test, measured from the ignition of the furnace, in minutes

After 10 minutes, the furnace temperature will be approximately 660 °C above the initial furnace temperature.

‘The flame barrier shall pass the test if no cracks, openings or other fissures have developed which would permit vision through the flame barrier or joint’ (BIA, 2001). Because the furnace temperature after 10 minutes is well in excess of the auto-ignition temperature of EPS, the metal skin of PIP performs a very important function in preventing the combustible panel core providing fuel to a fire.

3.5.2 Control of External Fire Spread

When PIP is used as an external cladding material, it must meet the heat release rate (HRR) criteria described in Part 7 of C/AS1. The requirements depend on the distance from the boundary of the external cladding, the building height and the building occupancy. Table 7.5 in C/AS1 summarises these requirements, and is reproduced in full herein as Table 3.5.2.1:

Building height	Distance to relevant boundary			
	Less than 1 m	1 m or more		
	All purpose groups	Purpose groups SC, SD	Purpose groups SA, SR	All other purpose groups
Single storey	A	–	–	–
Up to 7 m	A	B	–	–
Up to 25 m	A	A	B	B (Notes 1, 2)
Over 25 m	A	A	A	B
Key: The <i>external wall</i> cladding system shall have a peak rate of heat release and a total heat released not greater than given below for the applicable performance level (Note 3).				
	Peak Rate of Heat Release (kW/m ²)		Total Heat Released (MJ/m ²)	
	(Note 4)		(Note 4)	
A	100		25	(The smaller the heat release value the more stringent the requirement.)
B	150		50	
–	No requirement		No requirement	

Table 3.5.2.1 – Acceptable Heat Release Rates for External Cladding Systems

(Reproduced from BIA, 2001)

Samples are tested using the cone calorimeter method, as described in AS/NZS 3837 (SA/SNZ, 1998). The samples are subjected to a heat flux of 50 kW/m² for 15 minutes in a horizontal orientation, during which time the peak HRR and total HRR are measured.

Typical samples of PIP manufactured in New Zealand meet Class A, as stipulated in Table 3.5.2.1. This means that any PIP product, which has been tested, can be used in New Zealand as an external cladding material in any application.

3.5.3 Outbreak of Fire

Part 9 of C/AS1 provides various requirements for heat-generating appliances in relation to clearances, etc., from building materials. The intent, generally, of Part 9 is that steps be taken to ensure that any combustible building material not be

subjected to temperatures that exceed 75 °C. In relation to PIP, this criterion would ensure that the EPS core did not melt.

4.0 EXPERIMENTAL INVESTIGATION

The experimental phase of this project investigated the performance of PIP, and in particular the EPS core, when samples were exposed to thermal radiation from a metal radiating surface at elevated temperatures.

The configuration of the experimental procedure was intended to simulate a flue passing through a PIP ceiling or roof in a building.

All experiments were carried out at the University of Canterbury, in the Department of Civil Engineering Fire Lab.

4.1 Experimental Apparatus

4.1.1 Heat Source

The heat source for the experiment consisted of a 300 x 300 x 200 mm high stainless steel burner box. The burner box had a lid with a 150 mm diameter central opening and 50 mm high upstand which directed the flames directly up into the flue. The box was filled with kiln-fired clay spheres, approximately 20 mm in diameter, right up flush with the top of the upstand. The clay spheres produced flames on their upper surface, rather than within the box itself, thus preventing the burner box from overheating. The configuration of the burner box is shown in Figure 4.1.1.1:

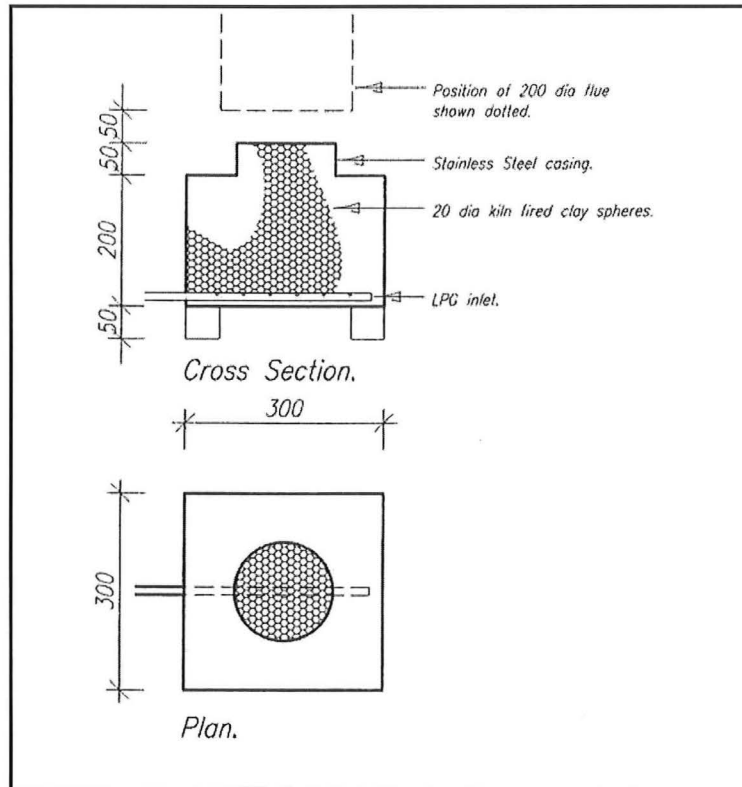


Figure 4.1.1.1 – Burner Box

The fuel for the burner was liquefied petroleum gas (LPG) which was fed into a 12 mm diameter diffuser tube at the base of the burner box. The LPG was drawn from the on site reticulated supply and controlled by an *MKS Instruments type 247* electronic mass flow control unit, shown in Figure 4.1.1.2:

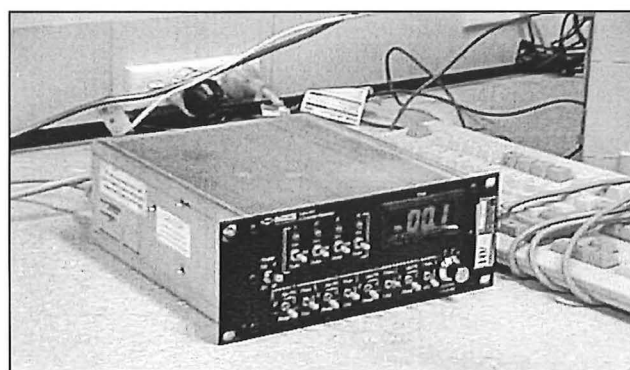


Figure 4.1.1.2 – Photo of Mass Flow Control Unit

The flow of LPG for each experimental run was varied, depending on the target surface temperature for the flue.

In addition to LPG, compressed air was also fed directly into the flue via a diffuser ring, which was fabricated from 12 mm tubing. The effect of the compressed air was to intensify the flaming within the flue and thus increase flue surface temperatures in a localised region. The compressed air diffuser ring was located internally, 100mm up from the base of the flue (refer Figure 4.1.2.1).

4.1.2 Cylindrical Radiator

The cylindrical radiator for the experiment was a length of “Spiroloc” 0.6 mm thick grade 304 stainless steel flue, with a nominal diameter of 200 mm. In order to concentrate the heat in the flue to a localised area, a series of internal baffles were welded into the flue, as shown in Figure 4.1.2.1:

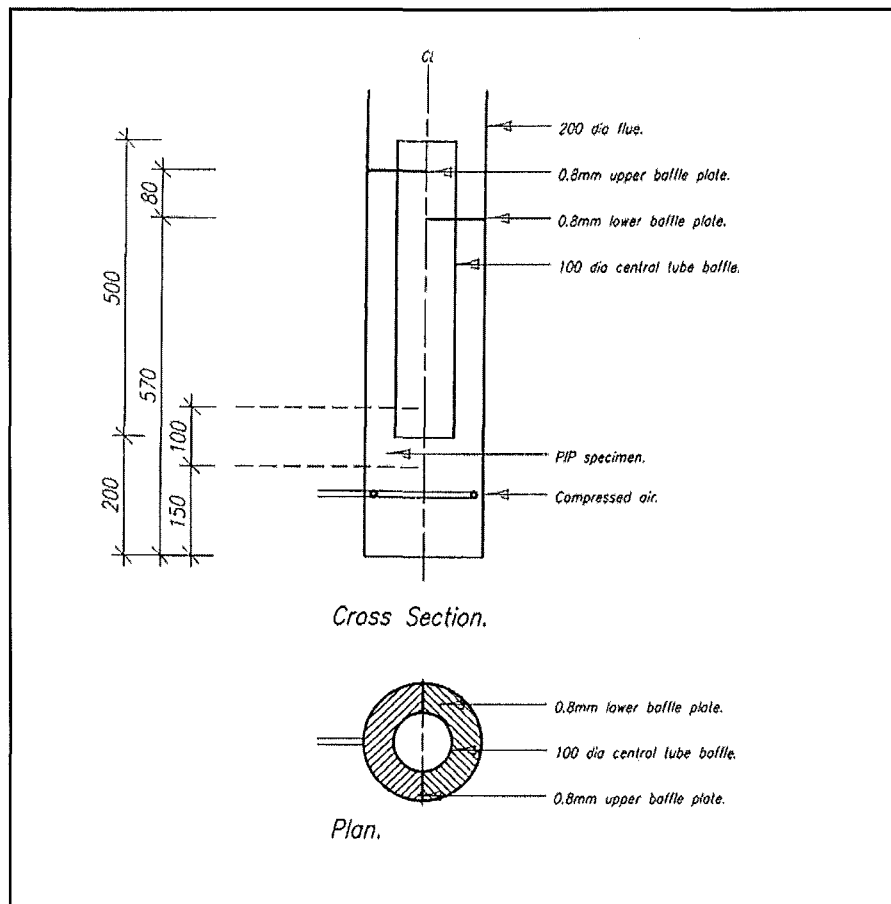


Figure 4.1.2.1 – Flue and Baffles

The reason for localising the peak flue surface temperature was so that the EPS core of the PIP specimens could be subjected to the maximum possible levels of thermal radiation. A series of six thermocouples welded to the flue over the height of the

baffle system provided surface temperature readings. In addition, a thermocouple was suspended within the flue to monitor the flame temperature.

For experiment No. 6 and No. 7, a piece of “Koawool” ceramic fibre blanket was also placed over the back face of the flue, in an effort to increase the temperature of the radiating surface.

The 1500 mm long section of flue was positioned in a vertical orientation, 50 mm above the burner box upstand. As shown in Figure 4.1.2.2, the flue and burner were fixed in positioned relative to each other by means of a steel support frame.

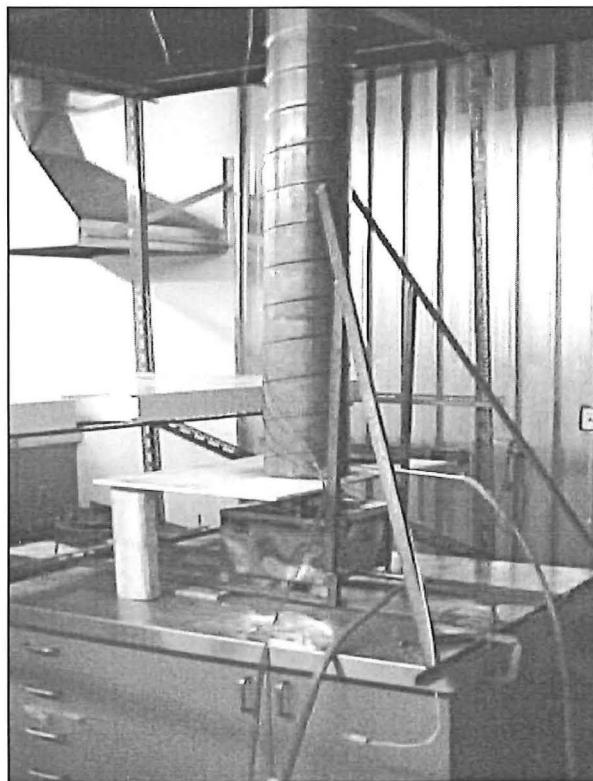


Figure 4.1.2.2 – Photo of Flue/Burner Configuration

This flue/burner framework was then placed on a moveable trolley that was wheeled into position once the PIP specimens had been set up.

4.1.3 Test Specimens

The test specimens consisted of pieces of 100 mm thick PIP supplied by a local manufacturer in Christchurch. The samples were 2400 mm long and a standard module width of 1200 mm.

Each panel specimen had a semicircular segment removed at the midpoint of one long edge. The diameter of this cut-out was nominally 20 mm more than the diameter of the flue, i.e. approximately 220 mm. Three vertical holes were also drilled in the top skin of the samples, to mid-depth, for the placement of thermocouples. The three holes were positioned at 100, 200 and 300 mm respectively from the surface of the flue on a radial line at right angles to the edge of the specimen. The two edges of the PIP specimen each side of the cut-out were capped with a metal flashing. The purpose of capping these edges was to simulate PIP panel that in reality would surround a flue, and to prevent combustible gases from freely escaping to the atmosphere. The preparation of the specimens is shown in Figure 4.1.3.1.

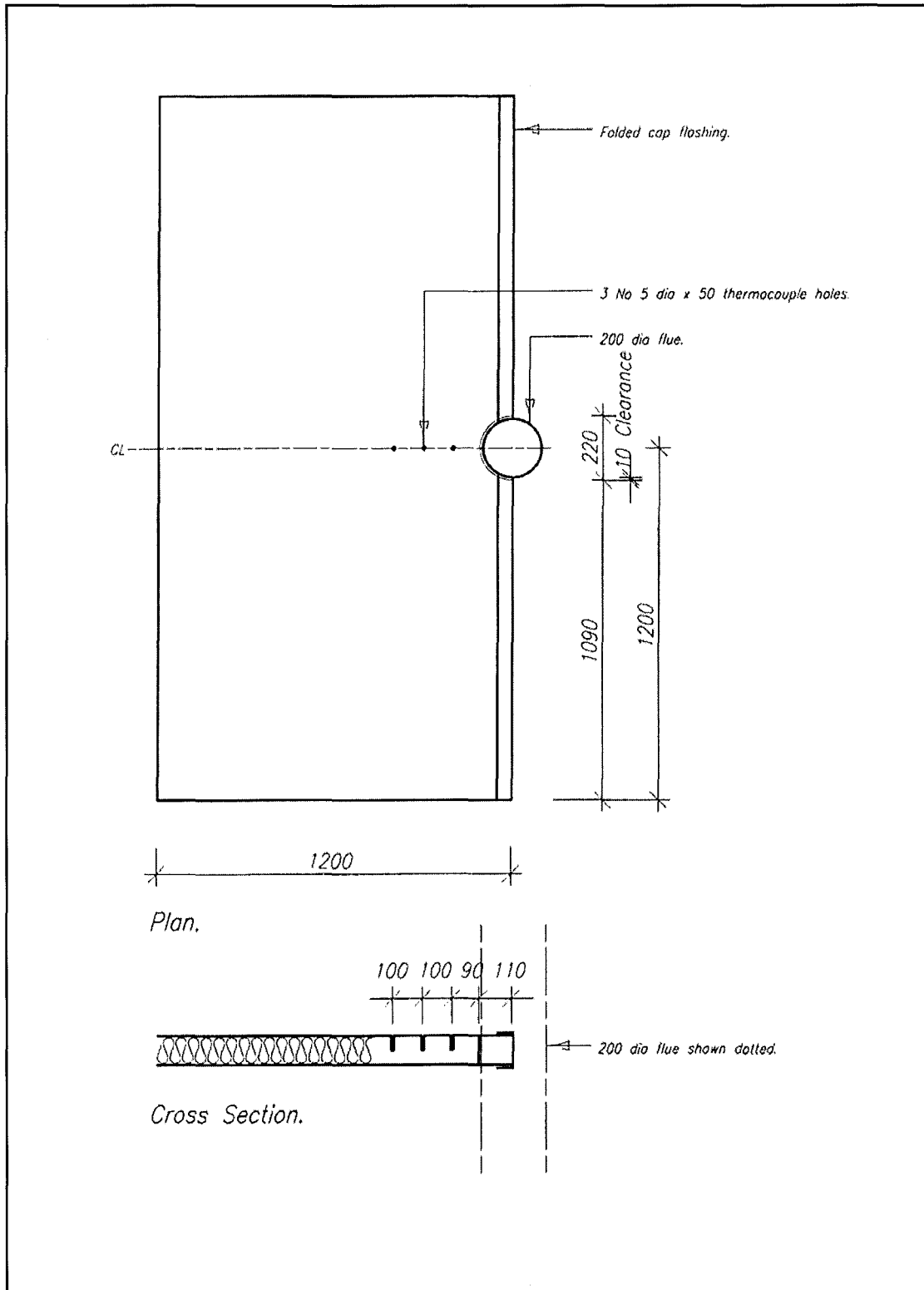


Figure 4.1.3.1 – Specimen Preparation

In all but the last experiment, the specimens were positioned horizontally, with the surface of the PIP normal to the vertical flue.

4.1.4 Support Framework

A lightweight frame was constructed by bolting together lengths of “Dexion” galvanised steel angle section. The frame was approximately 2400 mm by 1800 mm in plan, and approximately 3000 mm high. At approximately 1500 mm above floor level, cross members provided a support platform for the PIP specimens. The whole frame was stabilised by connecting the vertical corners back to the edge of the furniture calorimeter extract hood in the Fire Lab.

The purpose of the frame was to provide stable support for the PIP specimens, in relation to the flue radiator, during the experimental procedure. Figure 4.1.4.1 is a photo of the Dexion support frame with a PIP specimen in place:

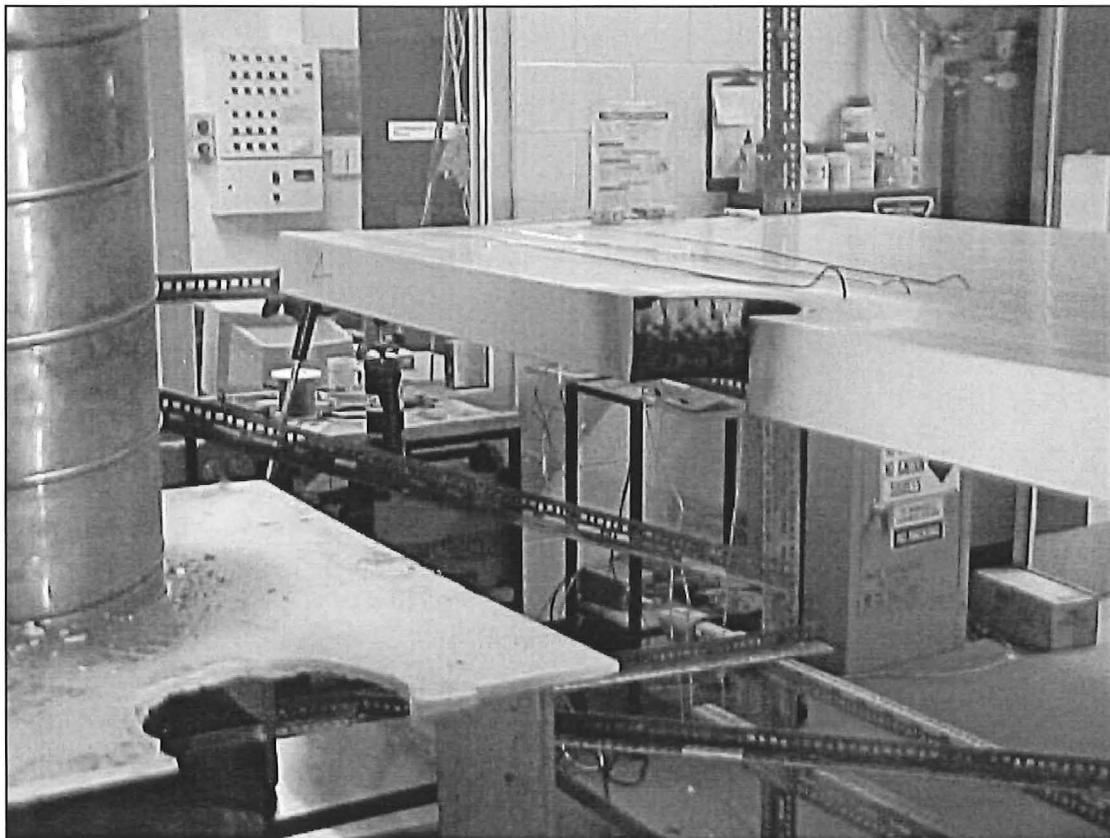


Figure 4.1.4.1 – Photo of Dexion Support Frame

Initially, it was also intended that the frame support the circular flue in a fixed position, but it was subsequently decided to have a moveable flue/burner arrangement. The reason for changing to a portable flue/burner was so that the specimens could be accurately located in the support frame and instrumentation positioned before they were subjected to the radiant heat source.

4.1.5 Instrumentation

Figure 4.1.5.1 shows the ten thermocouples that recorded temperatures during the course of the experiments:

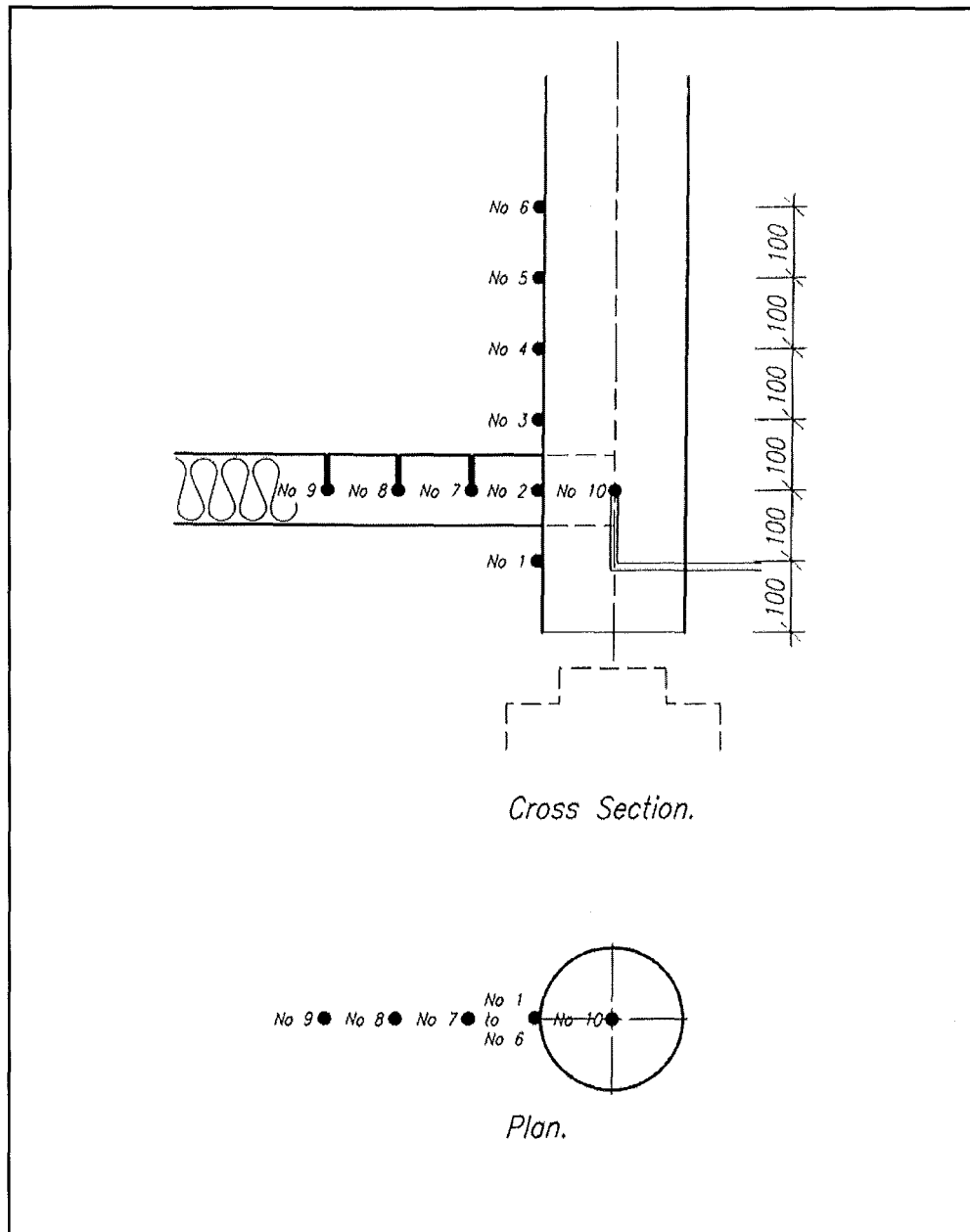


Figure 4.1.5.1 - Thermocouples

The type K24-GG thermocouple wire used in this experimental programme was manufactured by, B J Wolfe Enterprises. The thermocouple wire was American National Standards Institute (ANSI) type K. It consisted of two 24-gauge solid strands, one being chromal and the other alumin. Each strand had glass insulation, and the twin cores were in turn insulated with glass.

The six thermocouples on the surface of the flue were simply lengths of the type K wire welded to the surface of the flue. For the three thermocouples that were inserted

into the EPS core of the PIP, and the thermocouple within the flue itself, the thermocouple wire as contained within a 4 mm diameter stainless steel tube.

All ten thermocouples were connected to a data conversion box. At this point, the analogue voltage readings from the thermocouples were converted into a digital signal that connected to the serial port of a laptop computer. Universal Data Logger (UDL) software on the computer stored this data in Microsoft Excel format and provided a continuous readout of time vs. temperature, etc, during the course of each experimental run.

The UDL program collected data at a rate of 1 sample per second with no averaging.

4.2 Background Theory - Thermal Radiation

At a microscopic level, all matter contains charged particles. When these charged particles undergo acceleration, the energy possessed by the particles is converted into a form of energy known as electromagnetic radiation (Thomas, 1980).

Electromagnetic radiation covers a wide spectrum, ranging at the low end from cosmic rays through gamma rays, X-rays, ultraviolet radiation, visible light, infrared radiation, microwaves, radar and radio waves to ultrasonic electrical waves, as shown in Figure 4.2.1:

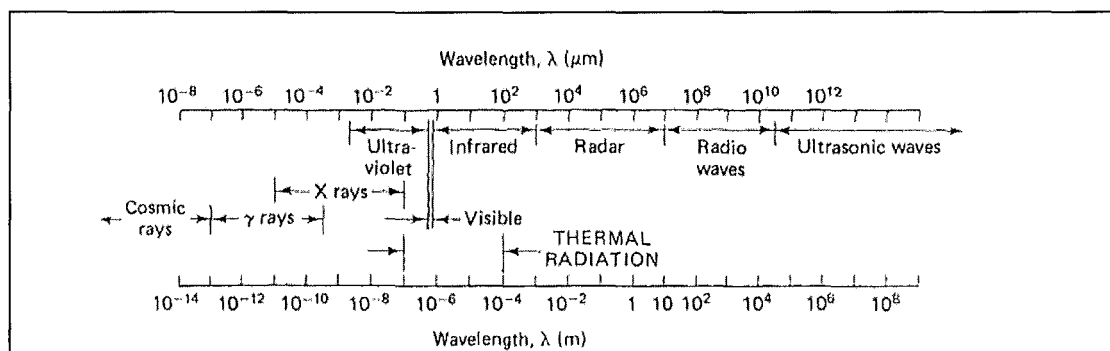


Figure 4.2.1 – Electromagnetic wave spectrum

(Reproduced from Thomas, 1980)

The various types of electromagnetic radiation are characterised by a frequency, ν , and a propagation velocity, c , that equals the speed of light in the medium, whether that medium be a solid, a liquid or a gas. The propagation velocity, c , is related to the speed of light in a vacuum, c_0 , by the refraction index, n , as shown in Eq. 4.2.1.

$$n = \frac{c_0}{c} \quad (4.2.1) \text{ (Sparrow and Cess, 1970)}$$

where

$$c_0 = 3 \times 10^8 \text{ m/s}$$

The index of refraction for air and most gases is essentially unity, but for liquid water and glass, $n \approx 1.5$ (Thomas, 1980).

The wavelength of the electromagnetic radiation, λ , is defined in Eq. 4.2.2.

$$\lambda = \frac{c}{\nu} \quad (4.2.2) \text{ (Thomas, 1980)}$$

There are various ways to produce electromagnetic radiation, depending on what type of charged particle is involved. Gamma or γ rays are produced by the fission of nuclei or radioactive disintegration. X-rays are produced by bombarding metals with high-energy electrons (Thomas, 1980; Özisik, 1973), while radio waves are the result of an alternating current flowing through an electrical conductor (Thomas, 1980).

One band of electromagnetic radiation depends on the temperature of the substance. This form of electromagnetic radiation results from the agitation of the microscopic particles that make up a substance (Siegel and Howell, 1972; Love, 1968). Because the energy associated with this agitation depends on the temperature of the substance, the resulting electromagnetic radiation is referred to as *thermal radiation*. 'In other words, thermal radiation represents the conversion of internal thermal energy of a substance into electromagnetic energy' (Thomas, 1980).

Thermal radiation is detected as heat or light (Siegel and Howell, 1972) and is in the intermediate portion of the electromagnetic spectrum shown in Figure 4.1.1, with a wavelength of 0.1 to 100 μm , or 10^{-7} to 10^{-4} m (Incropera and Dewitt, 1996). As depicted in Figure 4.2.2, the thermal radiation waveband includes ultraviolet radiation, with a wavelength of 0.1 to 0.38 μm , visible light, which has a wavelength of 0.38 to 0.76 μm , and infrared radiation, with a wavelength of 0.76 to 100 μm :

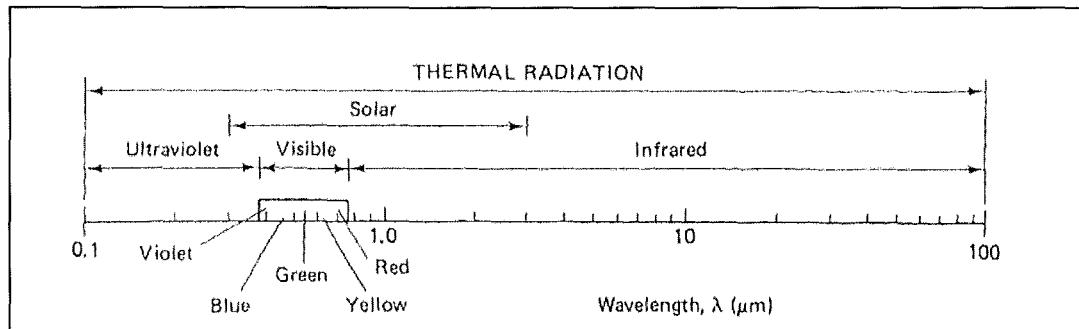


Figure 4.2.2 – Thermal radiation wavelength band

(Reproduced from Thomas, 1980)

Figure 4.2.2 also illustrates the fact that solar radiation falls in the thermal radiation waveband, with a wavelength of 0.3 to 3.0 μm .

Heat transfer by thermal radiation differs from conduction and convection in that it does not require matter, i.e. thermal radiation can occur in a vacuum (Incropera and DeWitt, 1996; Steward, 1974).

As well as a vacuum, the medium through which the thermal radiation passes can be a transparent gas, some form of liquid, or a solid material. Any object within the path of the thermal radiation will absorb or reflect the radiation, and if the object is transparent, it will transmit the incident thermal radiation. The absorptivity, defined by the symbol α , the reflectivity (ρ) and the transmissivity (τ) represent the fractions of thermal radiation incident upon an object that are absorbed, reflected and transmitted (Thomas, 1980). These three fractions must equate to unity, as indicated in Eq. 4.2.3:

$$\alpha + \rho + \tau = 1.0 \quad (4.2.3) \text{ (Steward, 1974)}$$

These three properties are dependent mainly on the temperature of the emitting object and the nature of the surface that receives the thermal radiation (Thomas, 1980) and can occur in different combinations. A dark surface is likely to have an absorptivity approaching unity, while the reflectivity and transmissivity will approach zero. A highly polished surface, conversely, will have an absorptivity and transmissivity of approximately zero, and a reflectivity of approximately one. It should be noted that these properties can vary with temperature, as illustrated by a shiny metal surface which may darken as it heats up, thus altering these three fractions.

Media that have an absorptivity and transmissivity approaching zero are termed nonparticipating media. A vacuum is a perfect example of this phenomenon, while common diatomic gases such as N₂, H₂ and O₂ meet the criteria almost exactly (Tien et al., 1995). Media that have a high absorptivity are termed participating media, of which carbon dioxide and water are examples.

A blackbody is an idealised object that has an absorptivity equal to unity that allows all incident radiation to pass into it, i.e. $\alpha = 1.0$, does not reflect any energy, i.e. $\rho = 0$, and absorbs internally all the incident radiation, i.e. transmissivity $\tau = 0$ (Siegel and Howell, 1972). A blackbody also emits the maximum possible thermal radiation at any given temperature (Özisik, 1973; Thomas, 1980). A blackbody therefore provides a standard for absorptivity and emissivity against which “real” surfaces can be compared (Thomas, 1980; Siegel and Howell, 1972).

An idealised blackbody emits radiant energy at a rate that is proportional to the fourth power of the absolute temperature of the emitting surface. The total emissive thermal radiation is a function only of the surface temperature (Siegel and Howell, 1972), and is given by the Stefan-Boltzmann law, given in Eq. 4.2.4:

$$E_b = \sigma T_s^4 \quad (4.2.4) \text{ (Thomas, 1980)}$$

where

E_b = total rate of thermal radiation emitted from a perfect radiator, W/m²

σ = Stefan-Boltzmann constant (5.67×10^{-8} W/m²K⁴)

T_s = absolute surface temperature, K

Some surfaces get close to being an ideal emitter, but a theoretically perfect blackbody does not exist. The emissivity, denoted by the symbol ε , relates the thermal radiation emitted by a blackbody to that emitted by a real surface, as shown in Eq. 4.2.5:

$$E = \varepsilon E_b \quad (4.2.5) \text{ (Thomas, 1980)}$$

where

E = thermal radiation emitted by real surface, W/m^2

ε = emissivity of real surface

The emissivity is a property of the material that is only dependent on the nature of the surface and its temperature. In other words, the emissivity does not remain constant over a range of temperature. The emissivity is a dimensionless parameter ranging in value from zero to unity. It can be deduced from Eq. 4.2.5 that as a real surface approaches being a blackbody, the emissivity will approach unity, and vice versa.

In relation to the experiments conducted as part of this project, the surface of the stainless steel flue discoloured as it increased from ambient to elevated temperatures. Correspondingly, its emissivity varied with temperature. Sparrow and Cess (1970) predict that the emissivity of stainless that is repeatedly heated and cooled will be in the range 0.5 to 0.7.

Only a fraction of the radiation that a surface emits will reach the receiving surface, with the balance passing into the surroundings. ‘The fraction of radiation leaving one surface which is intercepted by the other surface’ (Tien et al., 1995) is called the configuration factor, or shape factor, or view factor. The configuration factor essentially takes into account the geometrical relationship between the emitting and receiving surfaces (Buchanan, 1996), and is denoted by either the symbol ϕ or F_{12} , where the subscript number 1 represents the receiving surface and subscript number 2, the radiating surface. Therefore, the relationship between the radiation that one surface receives, and the radiation that another surface emits is given by Eq. 4.2.6:

$$E_R = \phi E_S$$

(4.2.6)

where

E_R = radiation received, W/m²

ϕ = configuration factor

E_S = radiation emitted, W/m² ($\equiv E$ in Eq. 4.2.5)

As with the emissivity, the configuration factor ranges in value from zero to unity.

By now substituting Eq. 4.2.5 into Eq. 4.2.6, the resulting Eq. 4.2.7 gives the radiation received:

$$E_R = \phi \epsilon \sigma T^4$$

(4.2.7)

It the experimental phase of this project, the EPS core of the PIP samples was subjected to radiant heat from a cylindrical flue. It is possible to analytically calculate the received radiation on the EPS core of the samples using configuration factor geometry and Eq. 4.2.7.

Blackshear (1974) provides the configuration factor for the geometry shown in Figure 4.2.3, which is a cylindrical radiator and a receiving surface parallel to the surface of the radiator:

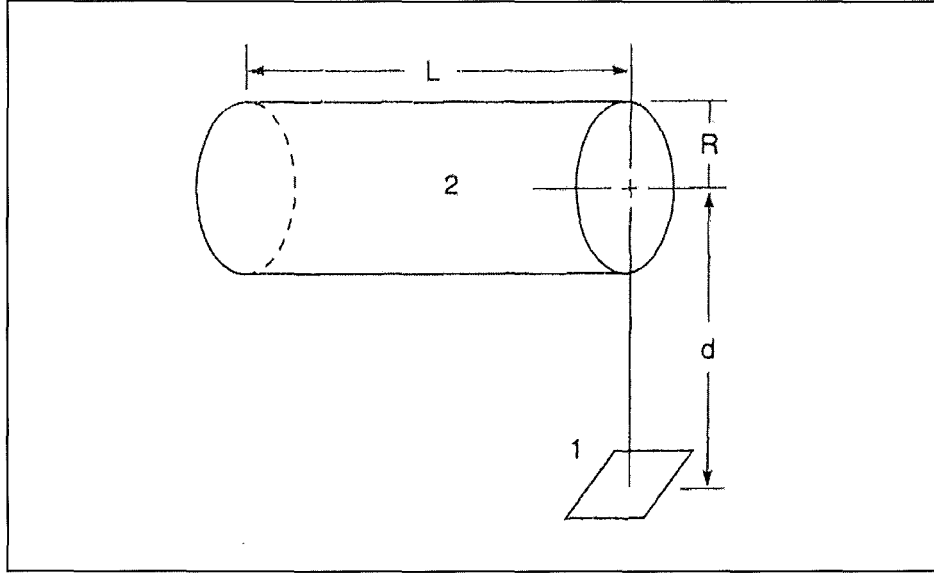


Figure 4.2.3 – Cylindrical radiator to parallel receiver

(Reproduced from NFPA, 1995)

The configuration factor for this geometry is given by Eq. 4.2.8 as:

$$F_{12} = \frac{1}{\pi D} \tan^{-1} \left(\frac{L}{\sqrt{D^2 - 1}} \right) + \frac{L}{\pi} \left[\frac{A - 2D}{D\sqrt{AB}} \tan^{-1} \sqrt{\frac{A(D-1)}{B(D+1)}} - \frac{1}{D} \tan^{-1} \sqrt{\frac{D-1}{D+1}} \right] \quad (4.2.8) \text{ (Blackshear, 1974)}$$

where

$$D = \frac{d}{R}$$

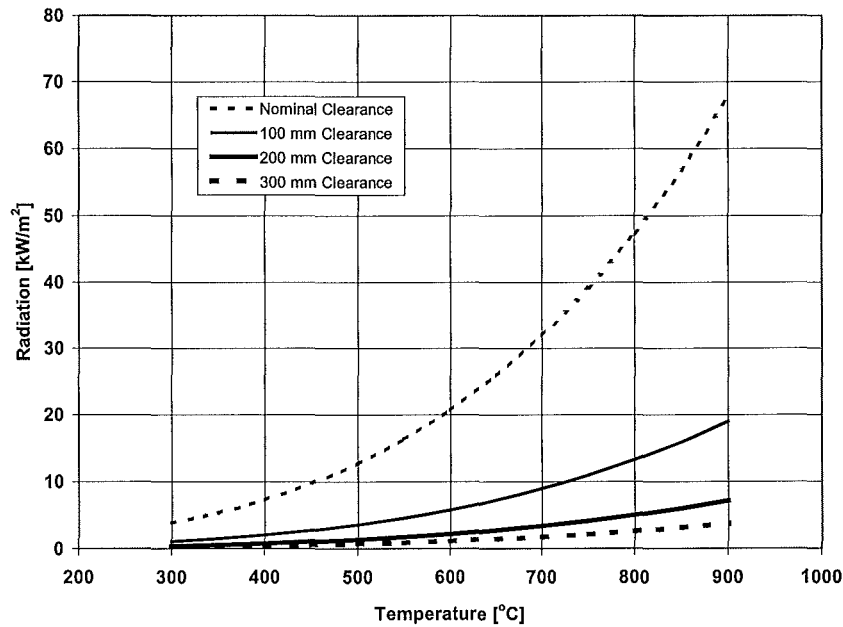
$$L = \frac{l}{R}$$

Based on the experiments conducted, the following input data was used to calculate the received radiation at various separation distances over a range of temperatures:

$R = 0.1$ m (half of 200mm diameter flue)

$L = 0.05$ m (half of 100 mm thick PIP)

$d = 0.11$ m (nominal clearance of 10 mm), 0.2 m, 0.3 m and 0.4 m



$\varepsilon = 0.7$ (Sparrow and Cess, 1970)

Figure 4.2.4 shows a graphical representation of these calculations:

Figure 4.2.4 – Flue Temperature vs. received Radiation on EPS Core

Consideration was also given to the radiation onto the metal skin of the PIP from the heated flue above and below the panel samples. The receiving surface is now at right angles to the cylindrical radiator, with the geometry shown in Figure 4.2.5:

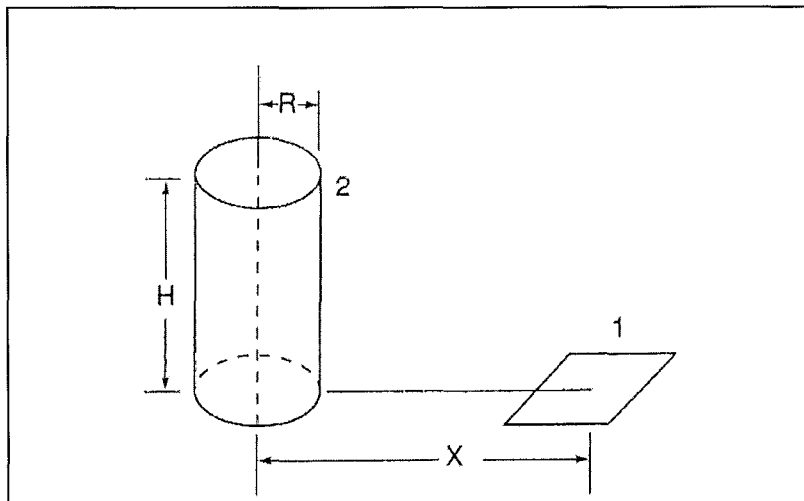


Figure 4.2.5 – Cylindrical radiator to normal receiver

(Reproduced from NFPA, 1995)

The configuration factor for this geometry is given by Eq. 4.2.9:

$$F_{12} = \frac{1}{\pi} \left[\tan^{-1} \sqrt{\frac{X' + R'}{X' - R'}} - \frac{(1.0 + X'^2 - R'^2)}{(1.0 + X'^2 + R'^2)} \tan^{-1} \sqrt{\frac{X' - R'}{X' + R'}} \right] \quad (4.2.9) \text{ (Blackshear, 1974)}$$

where

$$X' = \frac{X}{H}$$

$$R' = \frac{R}{H}$$

Repeated attempts to calculate the configuration factor using Eq. 4.2.9 continued to provide what would appear to be incorrect answers. It would seem logical that as the height of the radiating flue increased, so the received radiation would also increase. However, computing the configuration factor using Eq. 4.2.9 appeared to give the opposite trend. This method was subsequently abandoned in favour of approximating the cylindrical radiator as a rectangular plate, and using Eq. 4.2.10 to calculate a configuration factor.

$$F_{12} = \frac{1}{2\pi} \left(\tan^{-1} \frac{1}{Y} - \frac{Y}{\sqrt{X^2 + Y^2}} \tan^{-1} \frac{1}{\sqrt{X^2 + Y^2}} \right) \quad (4.2.10) \text{ (NFPA, 1995)}$$

where

$$X = \frac{a}{b}$$

$$Y = \frac{c}{b}$$

a = height of rectangular radiator

b = width of rectangular radiator

c = distance from radiator to receiver

To be able to use Eq. 4.2.10 as an approximation of a cylindrical radiator, it was first necessary to estimate what width of rectangular plate corresponded to a flue with a diameter of 200 mm. This was achieved by comparing values derived using Eq. 4.2.8

with the corresponding rectangular radiating surface, using trial and error. This process indicated that a rectangular radiator of width 40 mm had a reasonable correlation with a 200 mm diameter cylindrical radiator, over the temperature range 500 – 900 °C and clearances of 10 – 400 mm.

On this basis, the following input data was used in Eq. 4.2.10 and the results substituted into Eq. 4.2.7 to calculate the received radiation:

$$a = 0.25, 0.5 \text{ and } 1.0 \text{ m}$$

$$b = 0.02 \text{ (total width of radiator = } 2b\text{)}$$

$$c = 10, 100, 200, 300 \text{ and } 400 \text{ mm}$$

Figure 4.2.6 shows one example of the resulting output, being for a distance of 200 mm from the rectangular radiating surface:

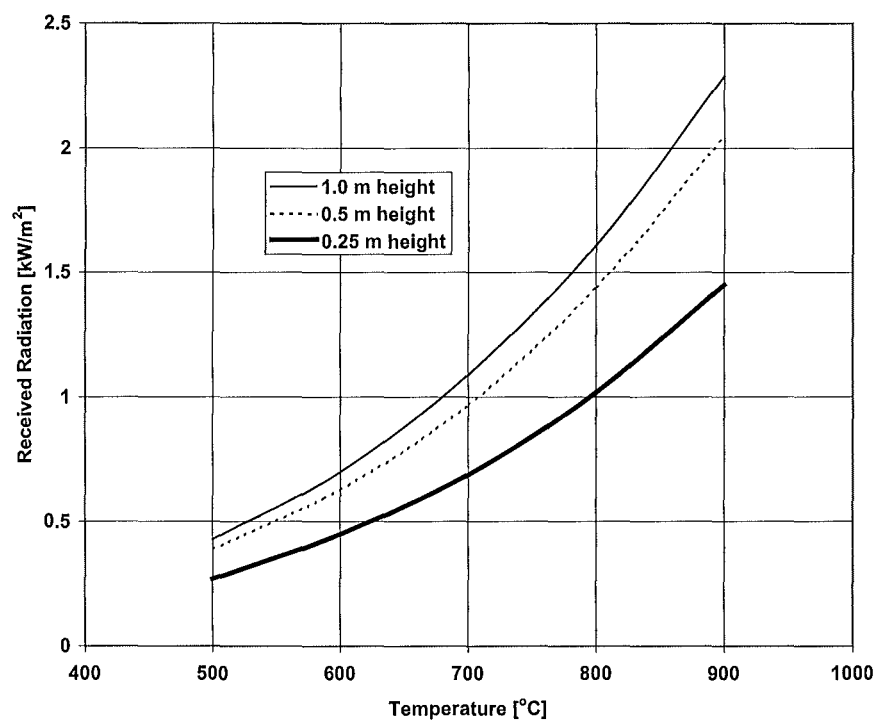


Figure 4.2.6 – Temperature vs. Received Radiation at 200 mm

The conclusion to draw from Figure 4.2.6 is that the height of the flue does not have a significant impact on the amount of radiation received on the surface of the PIP. On this basis, it was therefore considered that the length of the portion of flue above and below the faces of the PIP samples was not critical to the experimental objectives.

4.3 Experimental Methodology

The following procedure was followed for each experimental run:

- the specimen was prepared as described subsection 4.1.3
- the specimen was positioned on the Dexion support frame, the three thermocouples inserted into the pre-drilled holes and the exposed EPS core at the cut-out protected with a ceramic fibre blanket
- while at ambient temperature, the burner/flue was wheeled into position to confirm specimen alignment, and 10 mm clearance confirmed
- the burner was ignited and the UDL program started, but in non-acquisition mode, so as to monitor the flue surface temperature. Adjustments were made to the compressed air flow and fuel flow so as to reach the desired flue temperature
- as soon as the flue temperature for thermocouple No. 2 reached the desired level, the UDL program was restarted in acquisition mode. The programme timer was synchronised with a hand-held digital stopwatch
- at 30 seconds elapsed time, the video camera was started
- at 60 seconds elapsed time, the burner/flue was wheeled into position
- the specimen's performance was monitored, noting the time when ignition occurred, when flaming ceased, when the LPG was turned off, etc, as well as noting other general observations
- as the specimen cooled down, visual observations were recorded, capping flashing on edges removed, core melting measured, etc

In general, each test was terminated after 15 minutes in total, by stopping the flow of LPG to the burner. The test was allowed to continue if flaming combustion was still evident.

5.0 RESULTS

A total of nine separate specimens were tested in the course of the experimental programme for this project. This chapter of the report contains the results of those nine experiments, as well as some analysis of the data that was collected.

5.1 Experimental Observations

During the course of each separate experiment, a record was taken of all the information relevant to each test run, as well as observations of the behaviour of each specimen.

5.1.1 Experiment No. 1

This test run was essentially a trial that would indicate the likely behaviour of subsequent experiments. It also served as a way of establishing whether the proposed test methodology needed any modification. The following observations were made:

- achieved peak flue temperature $\approx 800\text{ }^{\circ}\text{C}$
- LPG flow 70 L/min
- Flue in place at 60 s
- Off-gassing immediately apparent
- Ignition at 150 s
- LPG turned off at $\approx 180\text{ s}$
- Flaming ceased at $\approx 240\text{ s}$
- EPS core melted back measured distance of 210 – 220 mm

5.1.2 Experiment No. 2

This second experiment was a full-length run that followed on from the initial trial, repeating exactly the same conditions of experiment No. 1. The following observations were made:

- Flue in place at 65 s
- Off-gassing visible almost immediately
- By 90 s, gas seeping from end of edge capping
- LPG turned off at 902 s
- No ignition occurred at any stage of experiment
- EPS core melted back measured distance of 410 – 450 mm

5.1.3 Experiment No. 3

The third experiment was a repeat of the first two experiments. Because no ignition had occurred for the second experiment, experiment No. 3 attempted to establish whether another sample could be ignited in a manner similar to experiment No. 1. The following observations were made during the third experiment:

- Flue in place at 69 s
- Slight misalignment of flue resulted in heated surface contacting EPS core and causing ignition. Flaming immediately ceased as flue was marginally repositioned
- Off-gassing evident straightaway
- Ignition of combustible gases on flue surface at 199 s
- Last small flame on edge of bottom panel skin flickered out at 863 s
- LPG turned off at 900 s
- EPS core melted back a measured distance of 450 – 600 mm

5.1.4 Experiment No. 4

The fourth test run investigated whether a lower flue temperature would still cause ignition of the EPS core. A reduced target flue surface temperature of $\approx 700\text{ }^{\circ}\text{C}$ was achieved by reducing the flow of LPG to the burner and adjustments to the compressed air flow in the flue. The following observations were made:

- LPG flow 45 L/min
- Flue in place at 66 s
- Off-gassing was noticeably less than for experiments No. 1 – 3, and consisted of a gradual build-up, rather than being instantaneous
- Ignition occurred at 406 s
- Flaming ceased at 730 s
- LPG flow terminated at 900 s
- EPS core melted back a measured distance of 300 – 500 mm

5.1.5 Experiment No. 5

Following on from experiment No. 4, the flue target temperature was further reduced to explore the relationship of ignition to flue surface temperature. The target flue temperature was therefore reduced to $\approx 600\text{ }^{\circ}\text{C}$. The following observations were made:

- LPG flow set at 40 L/min
- Flue in place at 65 s
- Faint traces of off-gassing at 105 s, gradually building in volume
- No ignition occurred throughout 900 s duration of experiment

Since no ignition occurred, the LPG flow was increased to 70 L/min at 900 s, in order to produce flue surface temperatures similar to those of experiments No. 1 – 3. Correspondingly, ignition occurred within approximately 120 s (at 1018 s elapsed time) of the fuel flow being increased. The flaming died down to be confined to the edge of the panel cavity within 360 s of ignition (\approx 1380 s of total elapsed time), and ceased some 720 s later (after 2100 s of total elapsed time). The LPG supply was cut at 2400 s. The EPS core of the PIP specimen had melted back approximately 550 – 750 mm

5.1.6 Experiment No. 6

For experiment No. 6 it was decided to attempt to increase the flue surface temperature. To do this, some 25 mm thick “Kaowool” ceramic fibre blanket was used to insulate the back face of the flue. The result was that the radiating surface of the flue increased by approximately 40 °C. An attempt was also made to increase the temperature with higher fuel flow rates, but this only resulted in highly unstable flue surface readings. The optimum was achieved for a fuel flow rate of 70 L/min. Thermocouple No. 7 was also used temporarily as a probe behind the Kaowool insulating blanket, and showed a surface temperature reading that approached the that of flame in the flue that was recorded by thermocouple No. 10. The following observations were made during the course of experiment No. 6:

- LPG flow at 70 L/min
- Flue in place at 60 s
- Ignition occurred within 5 s of flue placement
- Flaming ceased $t \approx$ 1380 s
- LPG flow turned off at 1500 s
- EPS core melted back a measured distance of 600 – 650 mm

5.1.7 Experiment No. 7

The seventh experiment was a variant of the sixth experiment. For this test, the EPS core of the PIP specimen was hollowed out a radial distance 100 mm back from the flue surface. The following observations were made:

- Flue in place at 67 s
- Small flash of flame at edge of cavity after 82 s, but then ceased
- Small flame appeared externally after 88 s, but again ceased
- Sustained ignition after 97 s
- After ≈ 600 s, sustained flaming ceased
- For the next 480 s approximately, between 600 and 1080 s, short-duration flaming started three more times
- LPG turned off at 1500 s
- EPS core melted back a measured distance of 600 – 750 mm

5.1.8 Experiment No. 8

Experiment No. 8 was a further variation on experiments No. 6 and 7. For this test, the affect of a flue temperature that increased from ambient was monitored. Instead of repeating the methodology of experiments No. 1 – 7, the unheated flue was positioned and the fuel ignited in place. The following observations were made:

- LPG flow turned on and ignited at 60 s
- At 225 s compressed air flow increased to stimulate the flue surface temperature
- Ignition occurred at 234 s
- External flaming receded within panel core cavity by ≈ 1320 s
- Small, intermittent internal flaming ceased at ≈ 1410 s
- LPG turned off at 1500 s
- EPS core melt back measured at a distance of 600 – 800 mm

5.1.9 Experiment No. 9

The ninth and final test in the experimental programme, differed from the previous eight in that the specimen was set up at a slope of 15 ° to the horizontal across the 1200 mm width of the PIP sample. The intention of this configuration was to make an assessment of how the EPS core of the panel behaved as it melted, i.e. did it flow, drip, etc? The settings, etc, were otherwise the same as for experiments No. 6 – 8. The following observations were made during experiment No. 9:

- Flue in place at 65 s
- Ignition occurred at 86 s
- Small droplets of burning, molten EPS dripped from panel cavity for approximately 60 – 120 s, with flaming of droplets ceasing almost immediately
- Coating on outer surface of top panel skin burnt for approximately 60 – 120 s
- Flaming around flue was most severe of previous test specimens
- After approximately 840 s, external flaming had retreated to the edge of the cavity between the panel skins
- Last flickering flame died out after approximately 1260 s
- Flaming appeared to decay more rapidly than previous experiments No. 6 - 8
- LPG turned off at 1500 s
- EPS core melted back a measured distance of 600 – 900 mm

5.2 Thermocouple Data

In this section of the report, the thermocouple data recorded for a selection of the nine test runs is presented. The balance of the data is contained in Appendix A1.0.

On each graph, the following five plots are shown, in the order of maximum to minimum:

- thermocouple No. 10, which was recording the flame temperature inside the flue
- thermocouple No. 2, which was the peak temperature on the outer surface of the flue. It also coincided with the midpoint of the PIP specimen
- thermocouples No. 7 - No. 9, which were the three thermocouples that recorded temperatures within the EPS core of the PIP specimens. These three thermocouples were located at radial distances of 100 mm, 200 mm and 300 mm respectively from the surface of the flue. They also provided an indication of when the EPS core melted

5.2.1 Experiment No. 6

The data from experiment No. 6 is of interest because it represents the most severe conditions that the specimens were exposed to during the testing programme. It is a combination of the highest flue surface temperature that was achieved, as well as the minimum EPS core clearance. As a result, the longest period of flaming combustion was observed during this experiment. Figure 5.2.1.1 is a plot of time vs. temperature for the five most significant thermocouples:

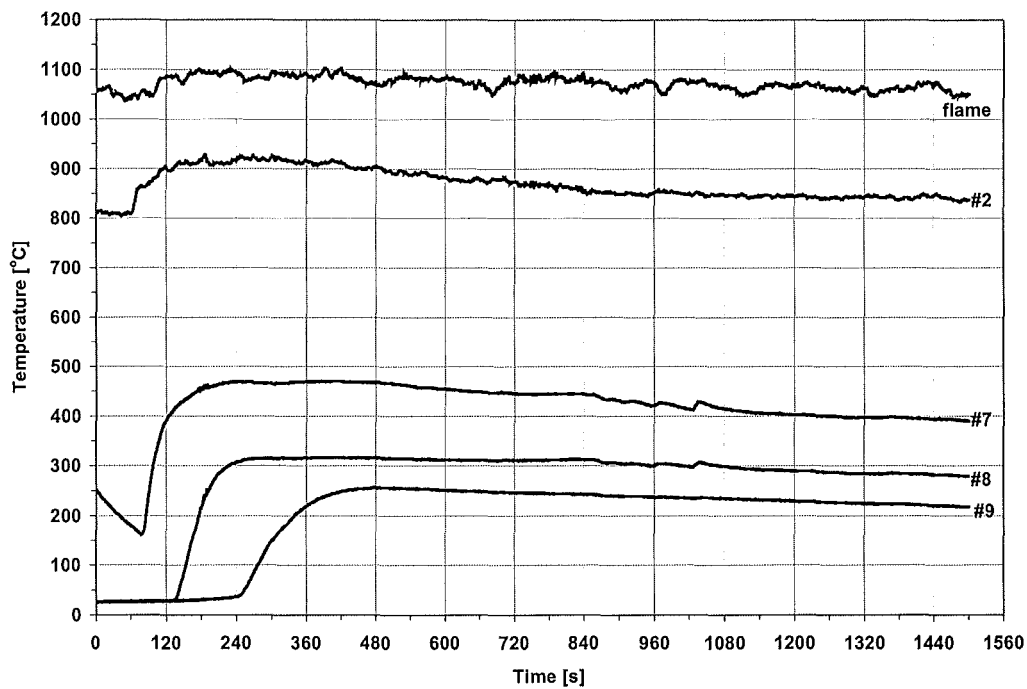


Figure 5.2.1.1 – Experiment No. 6 Thermocouple Data

There are a number of aspects worthy of mention in relation to the data shown in Figure 5.2.1.1. In relation to thermocouple No. 10, which measured the flame temperature in the flue, it can be seen that readings within a range of approximately 50 °C were maintained throughout the experiment. For thermocouple No. 2, the temperature rose approximately 100 °C as soon as the flue was positioned at an elapsed time of 60 s, and then gradually dropped to approximately 850 °C by the end of the test run. There was also a pattern for the three thermocouples buried in the core of the PIP specimen. It is clearly evident from the plot of thermocouples No. 7 – 9 when the radiant heat started to affect the temperature probes. As the heat progressed through the EPS core of the PIP specimen, the three thermocouples progressively started to register temperature increases. A peak of 471 °C occurred for thermocouple No. 7 at 405 s, while the peak for thermocouple No. 8 was 317 °C at 417 s and 256 °C between 472 and 523 s, for thermocouple No. 9. It should be noted that an anomaly appears in Figure 5.2.1.1 in that thermocouple No. 7 was used as a probe to monitor the temperature build-up behind the Kaowool lagging on the flue – insufficient time had been allowed for the thermocouple to return to ambient temperature before experiment No. 6 commenced.

5.2.2 Experiment No. 5

Experiment No. 5 represents the opposite extreme to experiment No. 6, with the lowest flue temperature of the entire test programme. The data is therefore of interest as being a lower bound. Ignition did not occur during the initial 900 s exposure for this test run. Figure 5.2.2.1 shows the time vs. temperature data for the five most significant thermocouples:

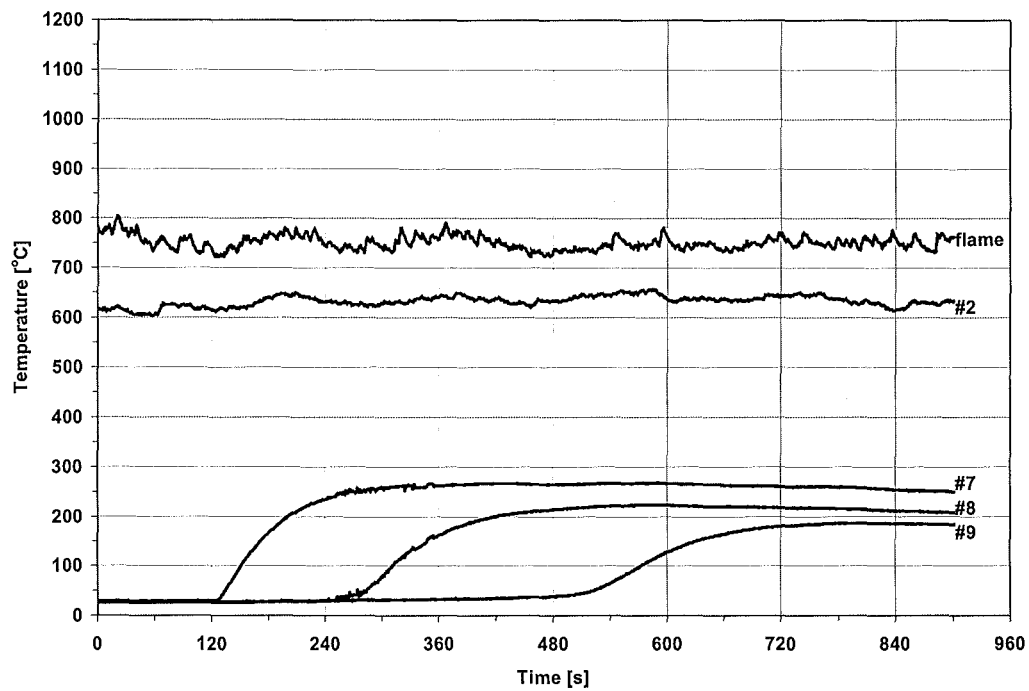


Figure 5.2.2.1 – Experiment No. 5 Thermocouple Data

With reference to Figures 5.2.1.1 and 5.2.2.1, there are some noticeable differences in the corresponding thermocouple readings between experiment No. 6 and No. 5. The flame temperature and flue temperature are noticeably lower for experiment No. 5, being approximately 300 °C and 200 °C lower, respectively. The flue surface temperature does not increase as much as for experiment No. 6 when the flue is positioned. The three thermocouples in the EPS core of the PIP specimen took longer to react, increased at a slower rate, and achieved significantly lower peak values.

5.2.3 Experiment No. 9

The ninth, and final, experiment in the programme included an interesting variation on the previous eight test runs. For this final experiment, the specimen was placed at an angle of 15 ° to the horizontal so as to simulate the pitch on a roof in an actual building. Data recorded for this experiment is shown in Figure 5.2.3.1:

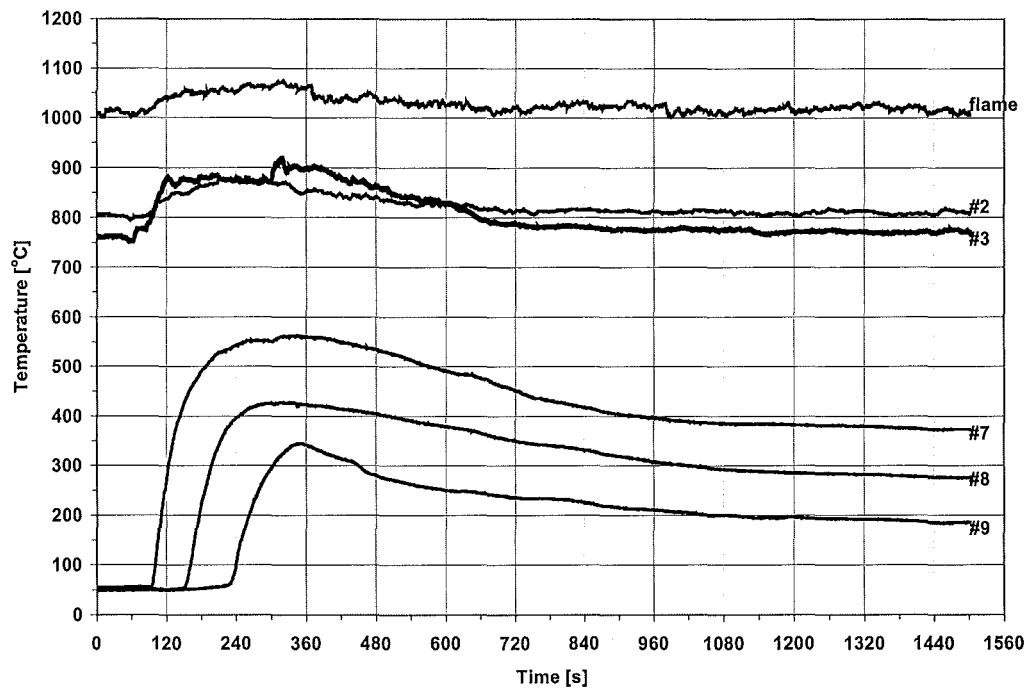


Figure 5.2.3.1 – Experiment No. 9 Thermocouple Data

There are a number of differences in the data shown in Figure 5.2.3.1 when compared to that for experiment No. 6, shown in Figure 5.2.1.1. The placement of specimen No. 6 at an angle meant that thermocouple No. 2 was no longer centrally located in relation to the EPS core. Thermocouple No. 1 was now closer to the core centreline. It was however thermocouple No. 3 which recorded the highest flue surface temperatures, and is therefore included as an extra plot in Figure 5.2.3.1. . The flaming for experiment No. 9 was more intense, but of shorter duration, than that for experiment No. 6. This is illustrated by the plot for the three thermocouples embedded in the EPS core, which peak slightly more rapidly, reach higher levels, and decay more quickly, than for the corresponding readings in experiment No. 6.

5.3 Analysis of Data

The experimental programme described in this report did not produce significant quantities of data. With only three thermocouples recording data within the EPS core of the PIP specimens, it is not possible to make any conclusive analytical findings. However, it is possible to analyse the available data and comment on the observed behaviour of the EPS core when subjected to radiant heat.

The data from experiments No. 2 – 6 is analysed, because the only variable in this consecutive series of tests was the flue surface temperature. Otherwise, each of these five test runs were essentially identical.

5.3.1 Regression of Core

From the data that was gathered during the course of each experiment, it is possible to estimate the rate of regression of the EPS core. With reference to the discussion in sub-section 3.4.1, a temperature of 100 °C was used as the temperature at which the EPS core started to degrade. From the time/temperature data for each experiment, and knowing the position of the thermocouples, it was possible to calculate average regression rates over three 100-mm regions of the EPS core. The first region was 0 – 100 mm from the flue surface, the second 100 – 200 mm, and the third 200 – 300 mm. Based on the method describes in section 4.2, the heat flux was then calculated at the mid-point of the regions for the average temperature over the associated time period. This analysis is represented graphically in Figure 5.3.1.1:

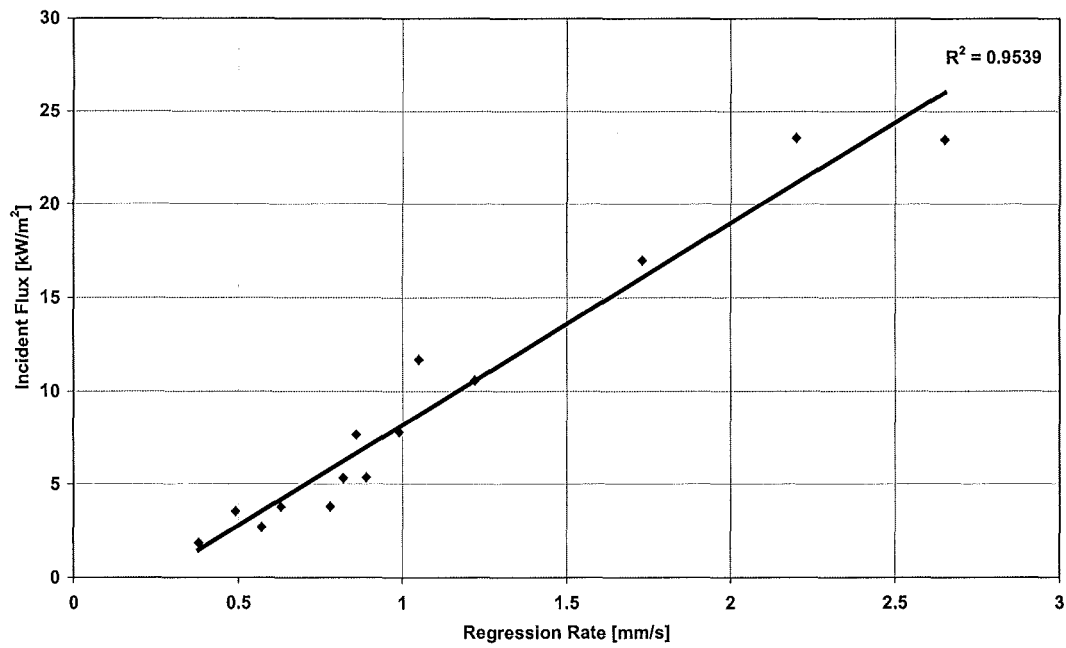


Figure 5.3.1.1 – Regression of Core vs. Incident Flux

The straight trend line correlates reasonably well with the data over the range shown. Intuitively, however, it would be expected that the line would intersect the y-axis at a value above zero. A straight trend line therefore would not apply for low incident flux levels, as it is logical to assume that the EPS core would not degrade at small incident flux levels.

5.3.2 Critical Incident Flux

Using the same raw data described in subsection 5.3.1, but excluding experiment No. 5, it is also possible to estimate the critical incident flux for the onset of degradation of the EPS core of the PIP specimens. Firstly, for each of the four experiments analysed, time vs. distance was plotted for each of the three thermocouple positions. An exponential curve of the general form shown in Eq. 5.3.2.1 was “manually” fitted to each set of data.

$$y = c(1 - e^{-kx}) \quad (5.3.2.1)$$

where

c = asymptote constant

k = constant

x = time variable

y = distance variable

The value used for the asymptote of the exponential curve was based on the actual melt back of the EPS core, measured at the end of each experiment.

Figure 5.3.2.1 shows the analysis for experiment No. 6 as an example of this process:

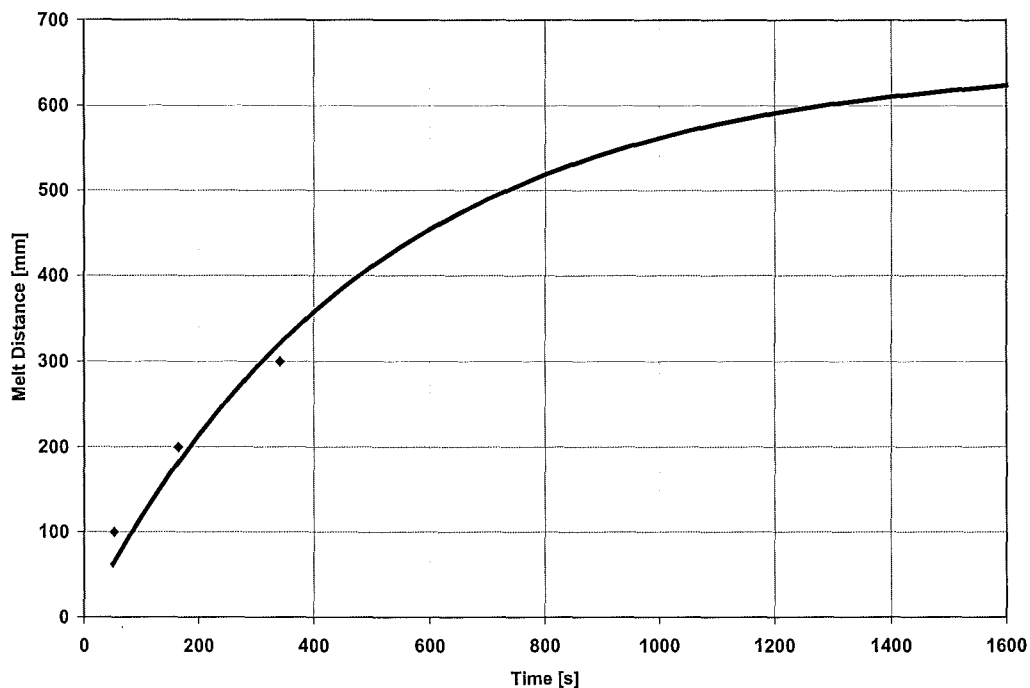


Figure 5.3.2.1 – Time vs. Melt Distance for Experiment No. 6

The remaining graphs for experiments No. 2 – 4 are contained in Appendix A2.0.

The asymptote value, along with the average flue temperature (thermocouple No. 2) over the duration of the experiment, could then be used to back-calculate the critical incident flux on the EPS core. These values for the four experiments analysed are contained in Table 5.3.2.1:

Experiment	Melt Distance mm	av. Temperature °C	Critical Melt. Flux kW/m ²
No. 2	450	795	1.27
No. 3	500	801	1.08
No. 4	500	713	0.76
No. 6	650	868	0.85

Table 5.3.2.1 – Critical Melting Flux

The average value for the critical melting flux is 0.99 kW/m².

The data contained in Table 5.3.2.1 can also be plotted as average flue temperature vs. melt distance, as shown in Figure 5.3.2.2:

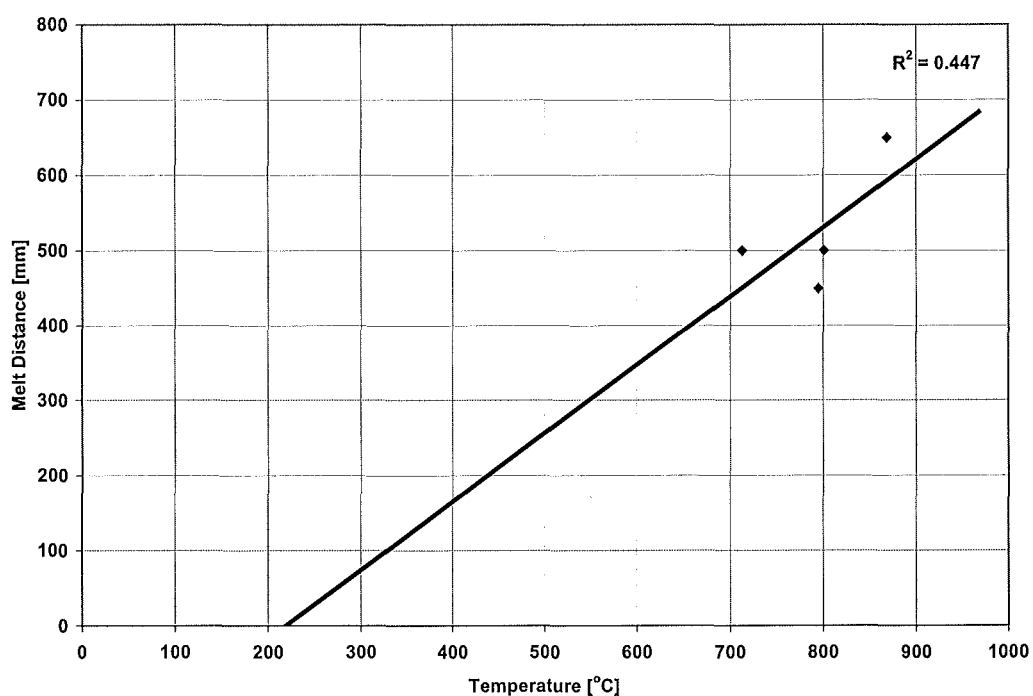


Figure 5.3.2.2 – Flue Temperature vs. Melt Distance

The amount of data on which Figure 5.3.2.2 is based is very small, especially at the lower end of the spectrum. It is therefore difficult to extrapolate the graph toward the lower temperatures with any degree of confidence. In theory the intercept with the x-axis should be the temperature at which EPS will start to melt. Even though the intercept is somewhat different to the actual value of 100 °C, the trend of the line is generally correct.

6.0 DISCUSSION

The objective of this report was to observe the behaviour of the EPS core of PIP specimens when subjected to radiant heat. Indeed this constitutes the bulk of the data gathered and subsequent analysis. The heating of the flue used as the radiant heat source during the experimental programme also provides some issues that are worth expanding upon.

6.1 Flue Surface Temperature

Considerable effort was expended at the outset of the experimental programme to achieve the desired levels of flue surface temperature. The original intention was to heat the flue surface up to 900 °C. The actual peak flue surface temperatures ended up being well short of this target. It was only ultimately possible to get slightly above 800 °C with a combination of baffling inside the flue, the introduction of compressed within the flue, and insulating the non-radiating part of the flue. And these elevated temperatures were only over a very localised region of the flue. The flue surface temperatures were significantly lower both above and below the baffling zone.

Flue surface temperatures in excess of 900 °C only resulted from direct flame impingement onto the flue from the burning EPS core gasses and not from the internal heating procedures.

The results of the experimental programme strongly suggest that for a real flue in a building, with a type of heat source similar to these experiments, it would be very difficult to achieve a flue surface temperature in excess of 600 °C. For this experimental programme, the flue surface temperature had to be artificially inflated in a manner that would be very unlikely to occur in real life.

6.2 Behaviour of EPS Core

The behaviour of the EPS core of the various PIP specimens was the primary focus of the experimental phase of this project.

6.2.1 Production of Combustible Gasses

As described in subsection 3.4.1, combustible gasses are produced from EPS when it is subjected to temperatures in excess of 200 °C. It is these combustible gasses that actually burn. With the flue surface temperatures for all of the test runs in excess of 600 °C, off-gassing occurred in each situation. It was clearly obvious from the experiments conducted that the rate of production of the combustible gasses was very temperature-dependent.

For example, with reference to the description given for experiment No. 5 in subsection 5.1.5, at a flue surface temperature of approximately 600 °C the off-gassing was very slow initially and rate only gradually increased. For experiment No. 5, the production of combustible gasses never reached the critical level required for ignition to occur.

By comparison, the production of combustible gasses for experiments No. 6 – 9 was significantly different, as described in subsections 5.1.6 – 5.1.9. Although optical density measuring equipment was not in use, it was noticeable that significantly greater volumes of combustible gases were produced at a much greater rate than for

experiment No. 5. Across the temperature range, off-gassing appeared to vary in proportion to the exposure temperature of the flue.

The metal capping flashings described in subsection 4.1.3 played an important role in the experiments. The purpose of these flashings was to concentrate the combustible gases in the immediate vicinity of the heated flue, and to not let the gasses escape into the atmosphere. In doing so, the chances of ignition occurring were increased, and the situation was more representative of a true PIP roof where the panel surrounded the flue. The seepage off gasses down the length of the flashings, that was noted in section 5.1, would be similar to what would occur down the length of a typical panel joint.

6.2.2 EPS Core Regression

From the data discussed in subsections 5.3.1 and 5.3.2, there are some obvious trends in the tendency of the EPS core to regress when subjected to radiant heat. In considering the data plotted in Figures 5.3.1.1 and 5.3.2.2, the data needs to be interpreted with caution so that misleading conclusions are not drawn. With regard to Figure 5.3.1.1, a plot of core regression vs. incident flux, the expectation would be that the EPS core could withstand a small level of flux before it started to recede. Although a straight trend line is reasonable over the range of experimental data, this line cannot be extrapolated to give a prediction of critical melting flux. Referring to Figure 5.3.2.2, which is a plot of flue temperature vs. melt distance, an extrapolation of the straight trend line intercepts the x-axis above the expected degradation temperature of 100 °C. The most likely explanation for this is that the amount of data is very limited and is therefore subject to uncertainty. In both cases the general trend is correct, in that the higher the temperature or flux, the greater the regression rate or melting distance. The data though is not accurate enough to make specific predictions.

6.2.3 Burning Behaviour

The actual burning behaviour of the EPS core was of the greatest interest during the experiments. A number of noteworthy features were observed.

In every single case, the flaming occurred in the immediate vicinity of the flue. There was no evidence of sustained flaming back inside the cavity created as the EPS core melted back from the flue. Only in one instance, in experiment No. 7, did any flaming occur away from the flue in the cavity. As illustrated in Figure A1.4, there was some brief flaming at thermocouple No. 8, located 200 mm back from the flue surface. Otherwise, the flaming combustion was restricted to a zone near to the flue surface. As the EPS core melted and formed combustible gasses, the gasses would only ignite spontaneously when there got close enough to the heated flue surface. As illustrated by experiment No. 5, if the flue surface was not hot enough, ignition would not occur.

Generally, the speed at which ignition occurred, the intensity of the burning, and the duration of the burning were all proportional to the flue temperature.

The next important observation noted was that in every case, the flaming died out after a period of time. There was absolutely no evidence of flame spread through the cavity away from the heated flue. This was most clearly demonstrated by the symmetrical pattern of the melt back observed in the test specimens after each experiment. The conclusion to draw from this is that the combustion process was fuel-controlled. Essentially what occurred was that as soon as the EPS core receded far enough away from the heated flue surface, and insufficient combustible gasses were being produced, flaming combustion ceased of its own accord. There was no intervention to cause the flaming to stop. Furthermore, the flaming died out even though the elevated temperature of the flue surface was still present. The inescapable conclusion to draw from this observation is that it is highly unlikely that a fire initiated at a radiant heat source will spread away from that heat source through the EPS core of the PIP.

The burning behaviour of the EPS core also exhibited some common enclosure effects. Firstly, as soon as the flue was positioned next to the PIP specimen, the temperature readings on the flue surface increased. Figure A1.1, which shows thermocouple data for experiment No. 2, clearly shows a jump in the temperature of thermocouple No. 2 as soon as the flue is positioned at 65 s. This is a good illustration of the point, because there was no flaming to distort the phenomenon. There is also some suggestion of ventilation-controlled combustion, with the combustible gasses burning at the edge of the specimen cut-out, or above the specimen on the heated surface of the flue. The more likely explanation however is that the combustion was more predominantly a function of temperature.

Experiment No. 8, the results of which are described in subsection 5.1.8, also illustrated this temperature dependence. Even though the EPS core would have gradually receded away from the flue surface as the flue temperature increased from ambient, ignition did occur when a high enough temperature level was reached. In other words, the rate that the heating of the core occurs may influence how quickly ignition occurs, but so long as the flue gets hot enough ignition will eventually occur.

Overall, the most dominant factor in the likelihood of combustion occurring was the surface temperature of the flue.

6.2.4 Sloping Specimen

Experiment No. 9 was conducted for the express purpose of observing the effect of a specimen orientated at a slope of 15° to the horizontal. The possibility was that the melting EPS core would flow towards the heated flue surface. As noted in subsection 5.1.9, more intense flaming did occur at the flue, and a small number of burning EPS droplets fell from the specimen, but the flaming died out more quickly than the other comparable test runs. In exactly the same fashion described in subsection 6.2.3, the burning of the combustible gasses was a fuel-controlled process. Because of the gravitational effects introduced by the sloping orientation of the specimen, the available fuel burnt more quickly and with greater intensity, but was also consumed more rapidly. The flaming therefore died out sooner than for experiment No. 6.

6.2.5 EPS Core Removal

As demonstrated by the description of experiment No. 7 in subsection 5.1.7, the removal of the EPS core prior to testing was ineffective in preventing ignition from occurring. A portion of the available fuel was removed in this way, and the onset of flaming was delayed, but the same end result occurred. The second half of experiment No. 5, described in subsection 5.1.5, illustrates this concept more graphically. Although the core would have melted approximately 300 – 400 mm away from the flue prior to the flue temperature being increased, ignition still did occur, albeit delayed. As discussed in subsection 6.2.3, the methodology of experiment No. 8, also supports this theory. There is an important lesson to learn from this particular finding. If done properly, removal of the EPS core of PIP can be effective. However, the practical constraints of being able to remove the core to a sufficient depth would usually render this method as being an ineffective fire safety measure when aiming to prevent ignition of the PIP core.

6.3 Further Research

The time limitations of this project did not permit a thorough or extensive experimental programme. The pioneering nature of the experiments provided insights that could not be explored further. A number of aspects merit further study:

- the influence of fuel load with the testing of specimens with a thicker EPS core
- multiple testing of some configurations to getting a more extensive basis for making analytical predictions
- a greater array of specimen thermocouples to detect temperature profiles further back into the specimen core, and more intensive thermocouples to record data at smaller intervals
- additional testing at lower temperature levels
- piloted ignition, instead of a spontaneous ignition situation only
- additional bench scale testing with a cone calorimeter to establish critical incident melting and/or ignition flux levels

7.0 CONCLUSIONS

The primary objective of this project was to study the behaviour of the EPS core of PIP when exposed to radiant heat.

The small amount of experimental data generated by the laboratory testing described in this report does not allow comprehensive analytical conclusions to be drawn.

It is possible however to make a number of general statements about the performance of EPS when used as the insulating core of PIP. These findings are no limited though to just PIP, but would be applicable to the general use of EPS as a building material.

The first and most obvious finding is that EPS is a combustible material. Whenever it is used in a situation where there is a possibility of exposure to elevated temperatures from fixed appliances, etc, steps should be taken to protect the EPS from such heat sources, and thus minimise the chance of the material initiating a fire. Limiting the temperature that the EPS core is exposed to, stipulated as 75 °C in Part 9 of Acceptable Solution C/AS1, would be a very effective step to take.

Secondly, the practise of removing the EPS core of the PIP around a flue penetration can have limited effectiveness, because of practical constraints. It is a very unreliable means to achieving compliance with the Outbreak of Fire provisions of the NZBC.

The third conclusion to draw from this project is that flame-retardant EPS will not support self-sustaining fire spread in the insulated cavity of PIP when the core is exposed to a direct radiant heat source. This finding even applies to levels of elevated temperature that are unlikely to occur in practice.

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APPENDICES

A1.0 Thermocouple Data

The following graphs are the balanced of the balance of the experimental data referred to in section 5.2:

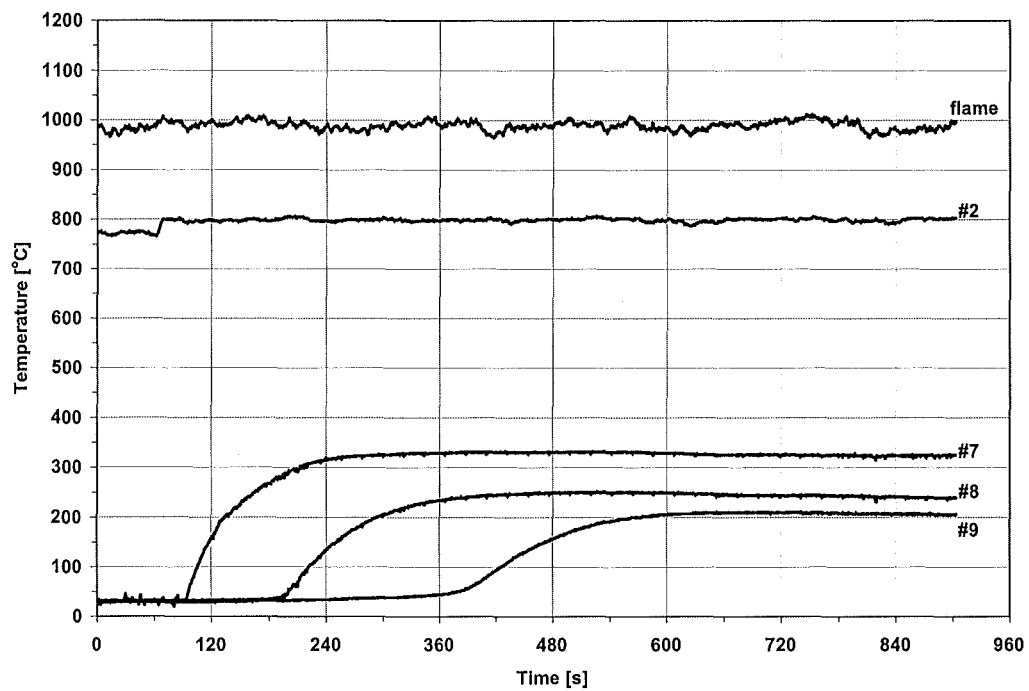


Figure A1.1 – Experiment No. 2 Thermocouple Data

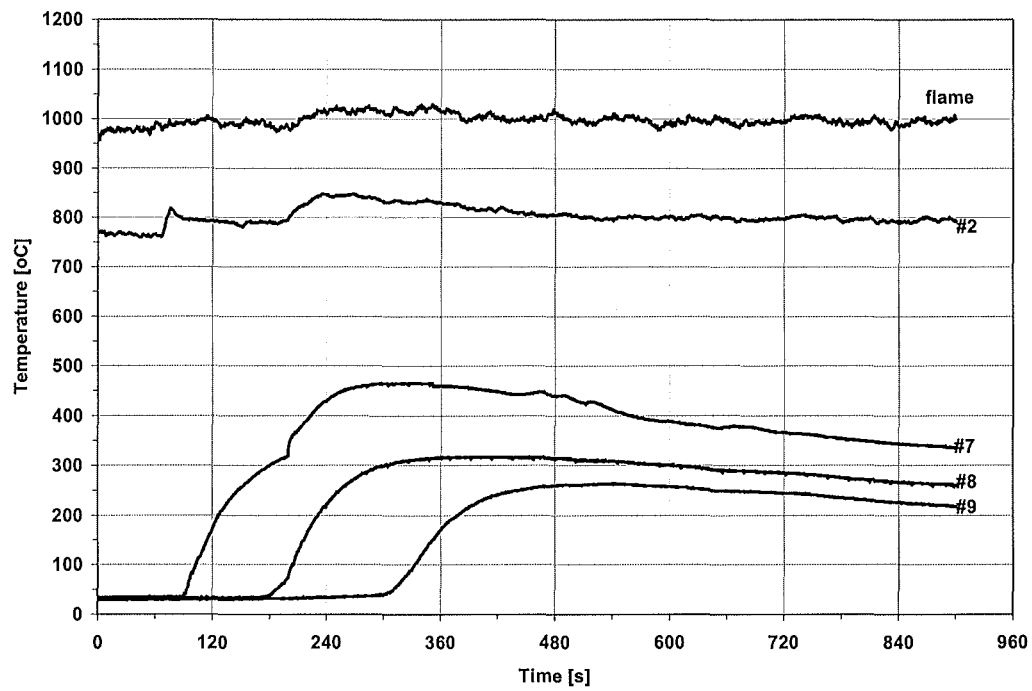


Figure A1.2 – Experiment No. 3 Thermocouple Data

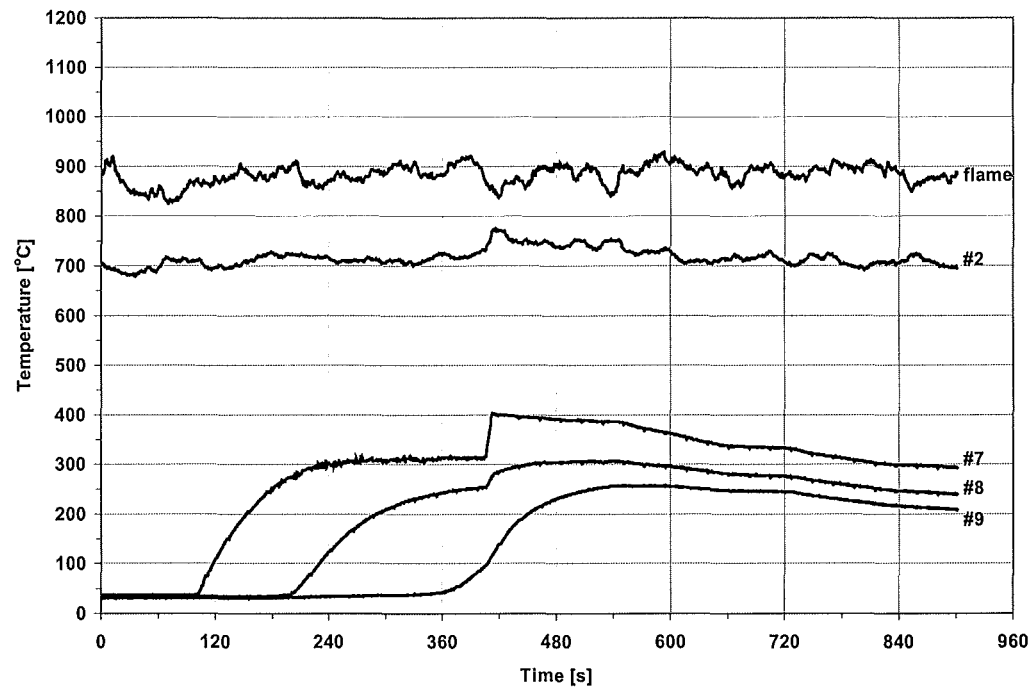


Figure A1.3 – Experiment No. 4 Thermocouple Data

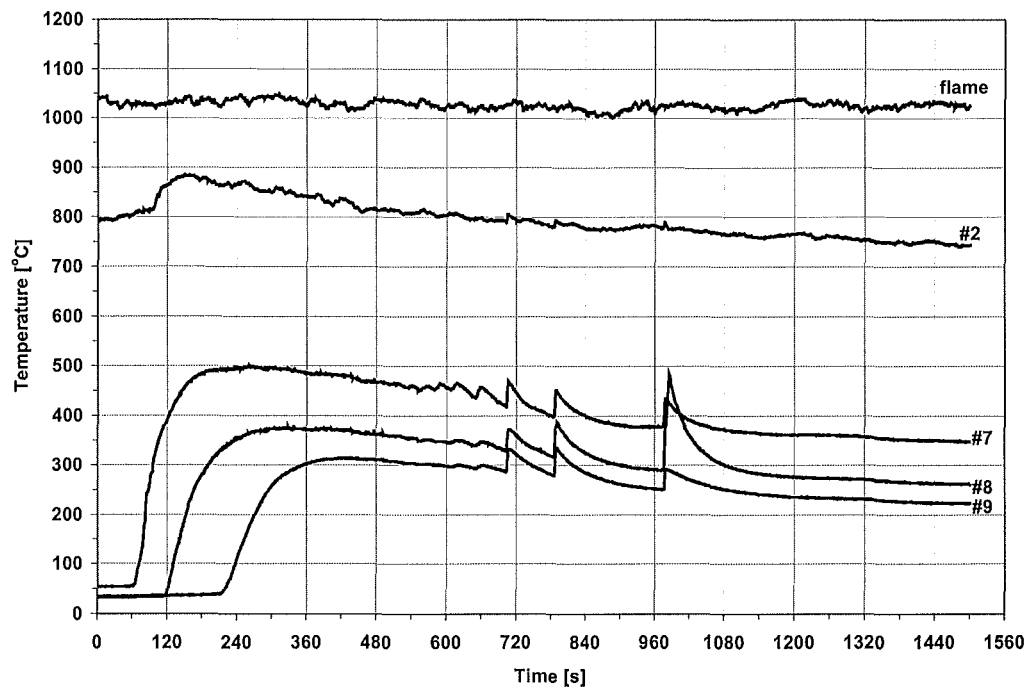


Figure A1.4 – Experiment No. 7 Thermocouple Data

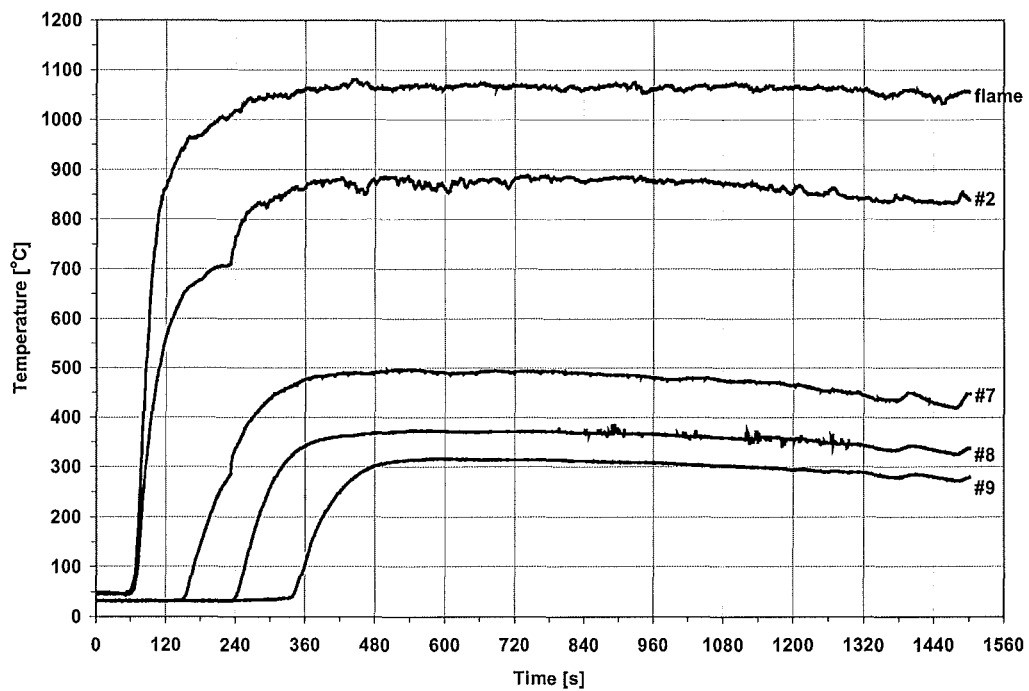


Figure A1.5 – Experiment No. 8 Thermocouple Data

A2.0 Time vs. Melt Distance

The following graphs are the balance of the data referred to in subsection 5.2.3:

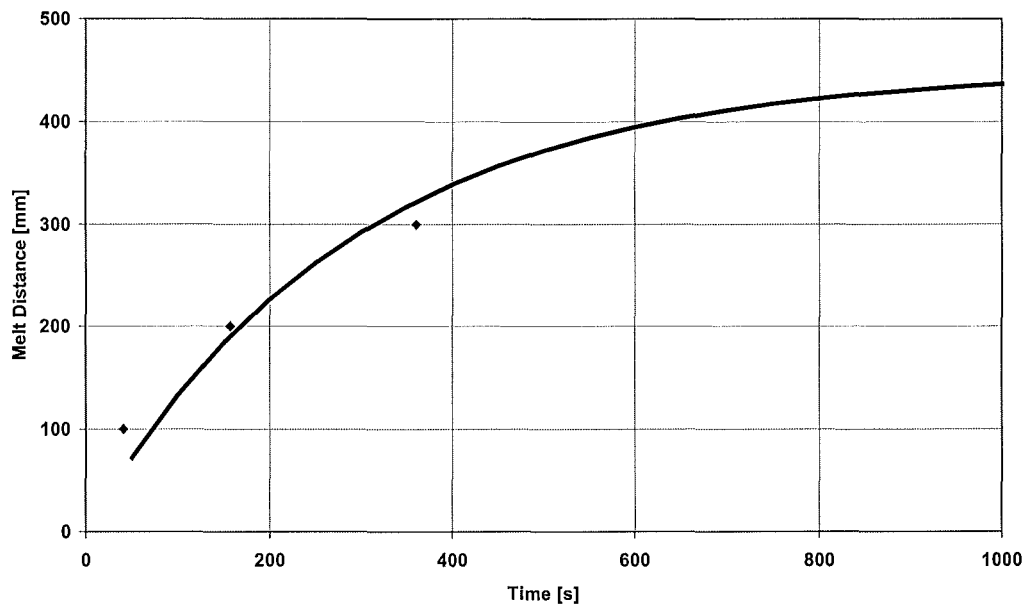


Figure A2.1 – Time vs. Melt Distance for Experiment No. 2

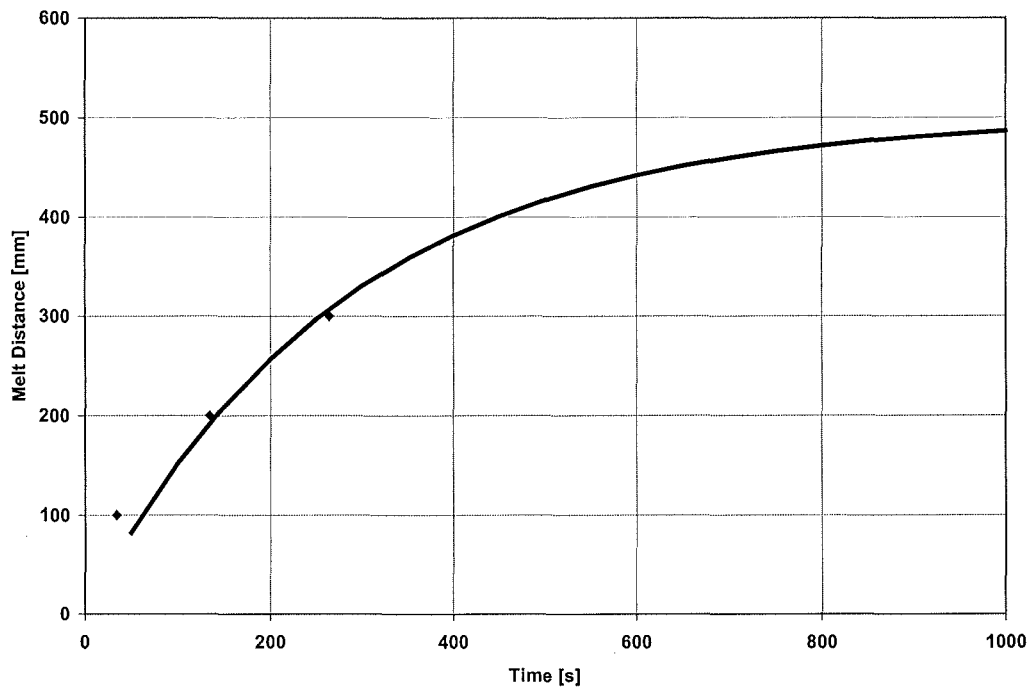


Figure A2.2 – Time vs. Melt Distance for Experiment No. 3

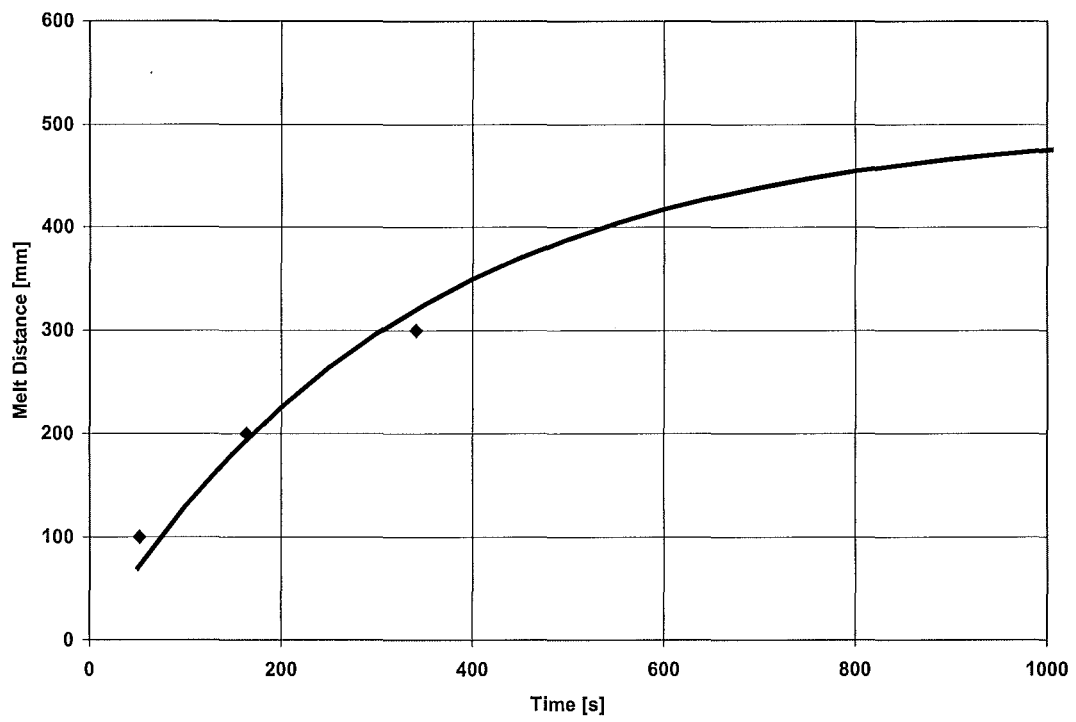


Figure A2.3 – Time vs. Melt Distance for Experiment No. 4

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